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Title: Changes in Landscape, Climate, and Life During the Age of Mammals: Interpreting Paleontology, Evolving Ecosystems, and Climate Change in the Cenozoic Fossil Parks

Abstract approved:

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This thesis develops a manual for interpreters at six National Park Service areas established to preserve and interpret fossils of the Cenozoic Era: Fossil Butte National Monument (Wyoming), John Day Fossil Beds National Monument (Oregon), Badlands National Park (South Dakota), Florissant Fossil Beds National Monument (Colorado), Agate Fossil Beds National Monument (Nebraska), and Hagerman Fossil Beds National Monument (Idaho). The manual will help interpreters place their park's story into the context of three components of paleoecosystems preserved in each park: changes in geologic landscapes, global climate, and the evolution of mammals. It also provides context for interpreting modern climate change. The colorful landscapes of the Cenozoic fossil parks preserve evidence of changing landscapes, climates, and life as well as clues about change affecting our future.

Because the six parks are nationally and globally significant paleontological sites, they also offer interpretive opportunities to connect visitors to the science of paleontology. The manual is written for interpreters with a variety of geology, other science and humanities backgrounds. The first three chapters provide a basic foundation of paleontological knowledge and interpretive resources applicable to all of the parks. Chapter 1 is an introduction to the scope and significance of the fossils and paleoecosystems preserved in each of the Cenozoic fossil parks. Chapter 2 outlines NPS interpretive theory and offers practical information for developing paleontology interpretation and interpreting long-term paleoecosystem evolution. Chapter 3 provides geologic content and interpretive methods for answering three common questions visitors ask: *How old are these fossils? What is a fossil?* and *Were all these fossils found here?* Interpretive responses to these questions allow visitors to connect with the Cenozoic Era, fossilization processes, and the profound sense of place afforded by the fossil parks. Chapters 4, 5, and 6 summarize how the major components of ecosystems changed between the extinction of dinosaurs 65 million years ago and the beginning of the Pleistocene "ice ages" 2.6 million years ago. Chapter 4 details the active geologic processes—mountain building and volcanic activity—of the American West during this time period and how these processes helped form and preserve the paleoecosystems of the parks. Chapter 5 places the parks' paleoecosystems in chronological order and

relates them to the global climate transition from the "greenhouse" world (nearly-tropical forests and lakes at Fossil Butte NM, John Day Fossil Beds NM, Badlands NP, and Florissant Fossil Beds NM) of 65 to 34 million years ago, to the "icehouse" world (cooler and drier woodlands, savannahs, and grasslands at John Day Fossil Beds NM, Badlands NP, Agate Fossil Beds NM, and Hagerman Fossil Beds NM) beginning 34 million years ago and continuing today. Chapter 6 traces the evolution of the horse during this time of global change from a four-toed, dog-sized browser to a hoofed, zebra-sized grazer on the grasslands of the American West. Chapter 7 describes the "ice ages" that followed the stories of the Cenozoic fossil parks. It also places the global climatic and ecosystem changes told by the Cenozoic fossil parks in the context of modern, rapid, anthropogenic climate changes. Each chapter includes "Digging Deeper" boxes that provide more detailed geologic content, or interpretive suggestions.

Changing Landscape, Climate, and Life During the Age of Mammals: Interpreting Paleontology, Evolving Ecosystems, and Climate Change in the Cenozoic Fossil Parks

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Jason P. Kenworthy, Author

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Changes in Landscape, Climate, and Life During the Age of Mammals: Interpreting Paleontology, Evolving Ecosystems, and Climate Change in the Cenozoic Fossil Parks

INTRODUCTION

The National Park Service (NPS) conserves and interprets our nation's most significant stories and landscapes. Reaching well beyond our 234-year history as a nation, rocks and fossils interpreted by the NPS record the ancient stories and landscapes that span hundreds of millions of years. Rocks and fossils from nearly every period of geologic time are found somewhere in the national parks. At least 224 parks preserve fossils either exposed in the rocks of the park, in the museum collections, or in a cultural context (such as in building stones or as American Indian historic objects; see Kenworthy and Santucci [2006]). Six currently-recognized fossil parks are the focus of this manual: Fossil Butte National Monument (Wyoming), John Day Fossil Beds National Monument (Oregon), Badlands National Park (South Dakota), Florissant Fossil Beds National Monument (Colorado), Agate Fossil Beds National Monument (Nebraska), and Hagerman Fossil Beds National Monument (Idaho). Collectively, they are referred to as the "Cenozoic fossil parks." The Cenozoic fossil parks interpret paleoecosystems (landscapes, climate, and life) from the Cenozoic Era, the past 65.5 million of Earth's 4,540 million-year history. The Cenozoic fossil parks span most of a period of geologic time from 65.5 to 2.6 million years ago, historically known as the "Tertiary period." Despite the fact that humans are mammals, the story of this "Age of Mammals" is not as familiar to most people as much older fossil animals such as trilobites (Paleozoic Era, 542 to 251 million years ago) or terrestrial dinosaurs (Mesozoic Era, 251 to 65.5 million years ago). The Cenozoic fossil parks contain many of the significant chapters of the Age of Mammals story in the western United States. They preserve a fantastic record of changing landscapes, climates, and life as well as clues about change affecting our future. This manual provides content and interpretive suggestions to interpreters at each of the six parks to help connect their park's story to the science of paleontology (Chapters 1–3), as well as ecosystem evolution and climate change during the Cenozoic Era (Chapters 4–6). The manual concludes with a discussion of how long term Cenozoic climate change provides context for natural climate change during the "ice ages" and modern anthropogenic (human-influenced) climate changes (Chapter 7).

American paleontology came of age in the late 1800s and early 1900s, fueled by unparalleled fossil discoveries in the western United States, particularly from the Age of Mammals. In fact, the first scientifically described fossil from the "West" was discovered in the 1840s in what has been known variously as *Mako Sica* to the Lakota Sioux, *Mauvaises Terre* to French fur traders, or translated into its more familiar form today: the Badlands of Badlands National Park. Hiram Prout's (1846, 1847) description of the jaw of a huge browsing mammal called a titanothere sparked interest in the fossil treasures of the West. More than 150 years later, fossils from all six of the parks continue to be studied. The Cenozoic fossil parks are both a place of historic paleontological significance and also the source of continued research and discovery. All of the parks except for Agate Fossil Beds NM have NPS paleontologists on staff. The parks are excellent places to interpret the science of paleontology and how paleontologists reconstruct the paleoecosystems preserved in the parks.

Chapter 1 of the manual is a guide to the scope and significance of the paleoecosystems preserved in each of the six Cenozoic fossil parks. In that chapter you will find nearly-tropical forests, expansive lakes, brushy savannahs, and open grasslands ranging in age from 52 to 3.2 million years old—but no dinosaurs! Chapter 2 explains NPS interpretive theory, and provides some tips and tools for paleontology interpretation in particular. Interpreters will also find a list of each park's primary interpretive themes and suggestions for additional themes based on information in the manual. Chapter 3 highlights interpretive opportunities associated with three questions commonly posed by park visitors: *How old is it?*, *What is a fossil?*, and *Were all these fossils found here?* Interpretive responses to these three questions can connect visitors to the Cenozoic time period, fossilization processes, and the significant sense of place achieved by interpreting fossils at the same place they once were living.

The Cenozoic fossil parks are not only fantastic museums of paleoecosystems, together they tell the story of a great change in Earth's climate. During the Age of Mammals, Earth transitioned from a "greenhouse" world (no ice sheets on either pole) to an "icehouse" world where enormous ice sheets advanced and retreated many times over the past 2.6 million years. The Cenozoic fossil parks span this transitional period. The oldest paleoecosystem addressed is a 52 million-year-old subtropical lake in Wyoming while the youngest comprises 3.2 million-year-old pine woodlands and open forests in Idaho. Each ecosystem is defined by its geologic foundation, local climate, and the animals and plants that lived there. The later chapters of the manual explore how all three of these components evolved during the Cenozoic Era.

Chapter 4 illustrates how the evolving geologic landscape of the American West formed the foundation for, and helped preserve, the paleoecosystems of the Cenozoic fossil parks. In that chapter you will discover the origin of the layers of sedimentary rocks found in the parks and see how volcanoes were vital to fossil preservation and determining the ages of the paleoecosystems. Chapter 5 relates the climates of the paleoecosystems of the Cenozoic fossil parks to the transition from greenhouse to icehouse. It shows how the pulse of Earth's climate correlates with reconstructions of the paleoecosystems. Chapter 6 explores the evolution of one popular family of animals—horses—during the Cenozoic Era. You will meet four-toed, collie-sized horses that lived in and near forests, three-toed horses eating mixes of leaves and early grasses, and the first member of the modern horse genus *Equus*, a true grazer built for speed. Each of these horses was adapted to the vegetation of their respective ecosystems.

Chapter 7 continues after the last paleoecosystem of the Cenozoic fossil parks, when great ice sheets advanced and retreated from both poles during the Pleistocene "ice ages." That chapter presents evidence of how human-influenced climate change could impact Earth's ecosystems on a large scale—but during a very short timeframe. Today we are living in a warm period following the most recent ice retreat, but on a cold Earth, especially when compared to the greenhouse ecosystems of the Cenozoic fossil parks.

This manual is designed to be a toolbox for interpreters at all six parks and is written for interpreters regardless of their background in geology. It contains scientific content as well as interpretive ideas and suggestions the author gleaned while working at the fossil parks. The manual is designed to provide some big-picture context for the particular chapter of the Age of Mammals story told at a given park, much like the Civil War parks of the NPS interpret not only the particular battle or event that occurred there, but also how those events tie into the larger stories of the American Civil War. Although designed to "stand alone," the chapters build upon one another, beginning with basic concepts and progressing to more advanced geologic ideas. Throughout the manual you will find "Digging Deeper" boxes providing additional geologic content or interpretive ideas, thoughts, or suggestions. The concepts can also be applied to the dozens of additional parks throughout the West that preserve fossil evidence of the Age of Mammals (Appendix A).

The manual incorporates interpretive methods and concepts developed by the author while working as an interpretive ranger at each park. The author started as a Student Conservation Association intern at Fossil Butte National Monument in 2001 and for most of the next two years he worked as a seasonal interpreter at the park. From 2003 through 2005, he worked off and on with the National Park Service primarily researching the scope and significance of paleontological resources throughout the NPS. In late 2005, he began working for the NPS Geologic Resources Division as a paleontology technician. He then enrolled at Oregon State University (OSU) in January of 2007. During the summers of 2007 and 2008, as part of his OSU thesis project, he spent between two and four weeks as an interpretive ranger at each of the other five Cenozoic fossil parks. Enjoy your time at these special places. They abound with opportunities for both visitors and interpreters to connect with ancient landscapes, changing climates, and evolving life during the Age of Mammals!

Chapter 1

There are no dinosaurs here: The Cenozoic fossil parks tell the stories of the Age of Mammals.

Hundreds of miles separate the colorful landscapes of Fossil Butte National Monument (NM), John Day Fossil Beds NM, Badlands National Park (NP), Florissant Fossil Beds NM, Agate Fossil Beds NM, and Hagerman Fossil Beds NM (Figure 1.1). The parks all exhibit eroded landscapes and experience hot summers, cold winters, and little rainfall. However, the fossils and rock layers reveal a variety of paleoecosystems: a 52 million-year-old subtropical, freshwater lake at Fossil Butte NM; a 34 million-year-old warm, temperate-subtropical lake at Florissant Fossil Beds NM; a 3.2 million-year-old cool, temperate riparian zone at Hagerman Fossil Beds NM; a variety of subtropical to savannah ecosystems from 44 to 6 million years old at John Day Fossil Beds NM. Separated in time and space by tens of millions of years and hundreds of miles, these ancient landscapes and fossil ecosystems appear to have little in common. But they each represent succeeding chapters of the story of life from just after the terrestrial dinosaurs went extinct 65.5 million years ago, until the “ice ages” began about 2 million years ago (Figure 1.2; for more on the geologic time scale, see Chapter 3). The fossils discovered within the Cenozoic fossil parks are significant not only because they are well preserved and abundant, but also because they include plants and animals that lived together in communities! These are among the best places in the United States to study paleontology—indeed, they helped redefine our understanding of the Age of Mammals.

A sign at the entrance to the museum at John Day **Fossil Beds**[1] NM states: “You will find no dinosaurs here. They are long dead. This is the Age of Mammals. And birds, flowering plants, fishes, beetles, insects, grasses, lizards, worms, clams, etc.” Although some visitors are disappointed to find out that there are no dinosaurs[2] found in the Cenozoic fossil parks, interpreters have an opportunity to connect visitors to animals more closely related to us: fossil mammals. Titanotheres, enteolodonts, oreodonts, nimravids, early beavers, three- and four-toed horses and so on are not the stars of many feature length films, but they certainly stir visitors’ imaginations. They represent a world vacated by dinosaurs and repopulated with mammals becoming more and more familiar to us as time goes on. The fossil plant record also includes many **families** and even some **genera** we would recognize today. Flowering plants (angiosperms) have been around for more than 120 million years and they take center stage in many of the Cenozoic fossil parks’ paleoecosystems. A new plant family—grass—expanded greatly during this time. When interpreting fossils at a given park, it helps to understand what sort of

[1] **Bold** terms are defined in the glossary.
[2] In this manual, the term “dinosaur” is used to refer to all non-bird dinosaurs. Most paleontologists classify modern birds as dinosaurs, so that some would say that all “terrestrial (land) dinosaurs” became extinct 65.5 million years ago at the close of the Mesozoic Era.

fossils are preserved at the other five parks and how that park's fossils compare to those found at the other parks. This chapter is an introduction to the varied paleoecosystems preserved in the Cenozoic fossil parks. The parks are presented in chronological order from oldest to youngest.

Fossil Butte National Monument, Wyoming

Fossil Butte and Cundick Ridge tower over Fossil Butte National Monument. The park was established in 1972 in the high desert of southwest Wyoming. Today, this region is a sea of sagebrush. The mean annual temperature is a mere 39°F (4°C) and only about one foot (30 cm) of precipitation falls per year. The 52 million-year-old ecosystems preserved in the rocks of Fossil Butte and Cundick Ridge record a much different environment, dominated by palm trees rather than sagebrush. There are two main groupings (or **formations**; see Box 1.1) of rock layers within the park: the primarily tan or brownish colored cliffs of the Green River Formation and the multicolored, striped, badlands of the Wasatch Formation (Figure 1.3). Deposited in a series of three subtropical lakes that covered most of southwestern Wyoming, northeastern Utah, and northwestern Colorado about 53.5 to 45.2 million years ago, the Green River Formation sediments are world famous for their well preserved and extremely abundant fossil fish (Grande, 1984; Smith and others, 2008). The monument preserves less than 2% of the at least 930 square mile (2,410 square km) deposits of Fossil Lake, the smallest but deepest of the three ancient lakes. The most common fossil fish, *Knightia eocaena* (a herring), is the state fossil of Wyoming and perhaps the most abundant articulated vertebrate fossil in the world (Figure 1.4). Twenty-two other fossil fish, including *Diplomystus* (herring-like but no close living relative), *Phareodus* (same family as today's Arawana), and *Lepisosteus* (same genus as modern gar fish) are also found. The most spectacular fossils come from the descriptively-named "18-inch layer." Many commercial quarries located outside of the park sell the fossil fish; nearly every rock shop in the country has Green River fossil fish. But the Green River Formation contains much more than just fish. There are alligators, crocodiles, turtles, stingrays, birds, and insects preserved in the Green River deposits. Some of the oldest bat fossils on the planet have also been found in the Green River Formation. A diverse plant flora including palm fronds nearly 7 ft (2 m) tall and hundreds of other species, is still being described (P. Kester, pers. comm., October 2009). The low, rounded, multicolored **badlands** of the Wasatch Formation contain mudstones, sandstones, and conglomerates deposited in the floodplains, streams, and deltas before, alongside, and after Fossil Lake dried up (Gunnell and others, 2002; Oriel and Tracey, 1970). Fragmentary mammal fossils, including a large **titanothere** (also called a brontothere), six-horned uintathere, and the earliest member of the horse family (commonly called "*Hyracotherium*"), are common in the Wasatch Formation. Fossil Butte's fossil record has attracted the attention of paleontologists and geologists since the late 1800s and provides the centerpiece for interpretation at the park (Buchheim, 1994; Buchheim, 1998; Cope, 1877, 1884; Grande, 1984, 1994, 2001; McGrew and Casilliano, 1975; Oriel and Tracey, 1970).

John Day Fossil Beds National Monument, Oregon

The rock layers at John Day Fossil Beds National Monument in central Oregon reveal systematic and profound ecosystem changes. None of the fossil parks interpret a longer or more complete record of time than John Day Fossil Beds NM. Studied since the 1860s, fossils interpreted and preserved within John Day Fossil Beds continue to inspire paleontologists. As University of California paleobotanist Ralph W. Chaney declared in 1948, "no region in the world shows more complete sequences of Tertiary land populations, both plant and animal, than the John Day formations." The park (authorized in 1974) encompasses three widely separated units within the John Day Basin: the Clarno, Painted Hills, and Sheep Rock units. The rocks and fossils interpreted by the park span 48 million years of the Cenozoic Era's 65.5 million years (Figure 1.2). The rock layers are divided into four formations that represent vastly different ecosystems: the Clarno Formation, the John Day Formation, the Mascall Formation, and the Rattlesnake Formation.

The oldest rocks in the park are found in the Clarno Unit and preserve paleoecosystems of the Clarno Formation, ranging in age from about 55 to 37 million years. Fossil fruits, nuts, seeds, leaves, and petrified wood from the 44 million-year-old Clarno Nut Beds are evidence of a nearly-tropical forest (with palms, grapes, abundant vines and bananas) in river deposits and volcanic mudflows (Figure 1.5) (Manchester, 1994). The Hancock Mammal Quarry contains a number of complete skulls and other fossils including 40 million-year-old turtle, alligator, the carnivore *Hemipsalodon*, early four-toed horses (***Haplohippus*** and ***Epihippus***), rhinoceros (*Telataceras*), tapir (*Protapirus*), and a large titanothere. These remains are preserved in river conglomerates and mudstones, perhaps from a point bar of a stream (Figure 1.6) (Fremd and others, 1997; Hanson, 1996; Lucas and others, 2004).

The wildly colorful, volcanic-ash-rich rocks and ancient soil layers of the John Day Formation are found in the Painted Hills and Sheep Rock units of the park. They range in age from 39 to 18 million-years-old (Figure 1.2) and are found in the Big Basin, Turtle Cove, Kimberly, and "Haystack Valley" members. The oldest rocks in the John Day Formation (Big Basin Member) contain deep red ancient soil layers (**paleosols**) typically formed in humid, tropical rainforests (Retallack and others, 2000). The yellows, reds, and browns in the 33 million-year-old Bridge Creek Flora (assemblage of fossil plants) of the Painted Hills contain evidence of cooler and drier ecosystems. These plant fossils indicate a temperate hardwood forest with *Alnus* (alder), *Betula* (birch), *Quercus* (oak), and *Metasequoia* (dawn redwood) growing in and around a swampy lake (Figure 1.7) (Meyer and Manchester, 1997). The green and blue rocks of the Turtle Cove Member contain evidence of ecosystems from 30.8 to 25.8 million years ago (Figure 1.8). A very diverse assemblage of dozens of different mammals, such as sheep-like oredonts, cat-like carnivores (*Pogonodon*), pig-like scavengers called **entelodonts** (*Archeotherium*), three-toed horses (*Mesohippus* and *Miohippus*), and early dogs, lived in the hardwood forests of the time (Fisher and Rensberger, 1972; Fremd and others, 1997). The pink and tan rocks of the Kimberly Member are about 26.8 to 24.2 million years old with fossils of **bear dogs** (*Daphaenodon*), entelodonts (*Daeodon*), three-toed horse (*Miohippus* and *Kalobatippus*), **oreodonts**, and many others (Figure 1.9) (Fremd and others, 1997). The tan and brown rocks of the youngest John Day Formation are part of the "Haystack Valley member." Hunt and Stepleton (2004) revised the "Haystack Valley" layers into four members with an age of 26.8 to about 18 million years old. Bear dogs, bizarre chalicotheres (***Moropus***), three-toed horses large (***Kalobatippus***) and tiny (***Archaeohippus***), tapirs, oreodonts, and rhinoceros (***Menoceras***) lived in desert scrubland, woodland, and the first sod grasslands in Oregon (Figure 1.10) (Albright and others, 2008; Retallack and others, 2000). The diverse assemblage of fossils and large number of datable volcanic ash layers in the Turtle Cove, Kimberly, and "Haystack Valley" members were used by Albright and others (2008) to revise the Arikareean North American land mammal age (more on land mammal ages in Chapter 3).

After immense floods of dark and runny **lava** from the Columbia River Basalt Group blanketed the landscape (Figure 1.11), ancient savannah-like ecosystems existed. Spanning about 3 million years from 16 to 12 million years ago (Figure 1.2), the volcanic-ash-rich paleosols, stream and lake deposits of the Mascall assemblages contain increased grass cover and dozens of fossil species. Some of the first elephant-like animals in North America (*Gomphotherium* and *Zygolophodon*, immigrants from Asia) as well as bear dogs, camels, and three-toed horses (***Merychippus*** and ***Parahippus***) roamed this increasingly grass-covered landscape (Figure 1.12) (Bestland and others, 2008; Downs, 1956).

The youngest rocks and fossils interpreted at John Day Fossil Beds are those of the Rattlesnake Formation. The 8 to 6 million-year-old paleosols and alluvial fan deposits (called **fanglomerates**) represent an ancient semi-arid grassland ecosystem. The Rattlesnake Ash Flow Tuff layer is evidence for a cataclysmic volcanic eruption 7 million years ago. This eruption blanketed 15,000 square miles (40,000 square kilometers) of Oregon, leaving behind the horizontal brown rock that now caps many of the bluffs south of the Sheep Rock Unit. Animals that would have fled such an eruption include the bear *Indarctos*, grazing hoofed horses like ***Pliohippus***, true dogs (*Canis*), and camels (Figure 1.13) (Fremd and others, 1997; Martin, 1983; Retallack and others, 2002). Fossils from the Rattlesnake were critical to the original description of the Hemphillian North American land mammal age (Figure 3.5) (Wood and others, 1941).

Badlands National Park, South Dakota

Eroded, fossil-rich, badland landforms are found throughout the world, but only at Badlands National Park do they merit a capital "B." Badlands of the Eocene–Oligocene White River Group (particularly the Chadron, Brule, and Sharps formations) contain a more or less continuous story of deposition from the late Eocene through the middle Oligocene, spanning 11 million years from 37 to 26 million years ago. This was a time of the great climate transition from a global "greenhouse" climate to a global "icehouse" climate. Badlands National Monument was originally authorized in 1929, and redesignated a national park in 1978. It contains more than 250 vertebrate species that are among the best preserved in the world for this time period, and certainly among the most studied. Today the park experiences a mean annual temperature of 50.5 °F (10.3 °C) and precipitation of 16.8 inches (42.7 cm), quite different than the conditions of the paleoecosystems preserved in the Badlands rock layers. The low gray hills of the Chadron Formation record a nearly-tropical, forested ecosystem. Huge rhino-like (but not related) mammals called "titanotheres" are so common early paleontologists referred to these rocks as the "titanothere beds." Although titanotheres are found in all of the Eocene-aged fossil parks, they were at their largest living in the paleoecosystems of the Chadron Formation. Aquatic turtles (*Graptemys*), alligators, small "running rhinos" *Hyracodon* and *Caenopus*, the sheep-like oreodont *Merycoidodon*, the "Big Pig" *Archaeotherium*, and the three-toed horse *Mesohippus* are also preserved in the 37 to 34 million-year-old layers (Figure 1.14) (Clark and others, 1967). The red and gray bands of the Brule Formation form most of "The Wall." They contain volcanic ash-rich sediments and represent one of the planet's greatest records of Oligocene life from 34 to 30 million years ago. Land turtles and oreodonts are so abundant that these beds were originally referred to as the "turtle and oreodont beds" (Figure 1.15). The Oligocene fossils are dominated by land tortoises and small oreodonts and the semiaquatic rhino *Metamyanodon*. The three-toed horses ***Mesohippus*** and ***Miohippus*** are also found here. Rhinoceros, camels, entelodonts, and a variety of rodents are also common (Clark and others, 1967; Prothero and Emry, 2004; Stoffer, 2003). The jagged uppermost peaks of Sharps Formation contain a record of life along streams in savannahs and steppes populated by oreodonts, saber-toothed cat-like animals, rodents and terrestrial beavers 30 to 26 million years ago (Figure 1.16). Dozens of ancient soil layers form the prominent color bands throughout the formations and provide a record of climatic change from warm and wet forests (Chadron Formation) to cooler and drier woodlands, savannahs (Brule Formation) and semi-arid savannahs or steppes (Sharps Formation) (Retallack, 1983).

Paleontology in the American West was born of such fossils from the "Big Badlands." In the mid 1800s, Hiram Prout, a dentist from St. Louis, provided the first scientific description of a fossil from the Chadron Formation and opened the eyes of paleontologists to the West (Figure 1.17) (Prout, 1846, 1847). The fossil mammals from Badlands NP and the surrounding area were used by Wood and others (1941) as part of the original description and characterization of the Chadronian, Orellan, Whitneyan, and Arikareean North American land mammal ages (see Chapter 3). The park also preserves marine fossils from the Mesozoic Era—the Age of Dinosaurs—creating opportunities to interpret mass extinctions and the evolutionary expansion of mammals (Boxes 1.2 and 1.3).

Florissant Fossil Beds National Monument, Colorado

Florissant Fossil Beds National Monument (established 1969) is in the shadow of central Colorado's Pikes Peak. At 8,400 ft (2,560 m) Florissant is the highest of the Cenozoic fossil parks and the coldest—the mean annual temperature is only 39.6°F (4.2°C) with rainfall of about 15 inches (37.5 cm). Visitors today stand beneath 90 ft (27 m) ponderosa pines but among 34 million-year-old fossil stumps of giant redwood trees that were three times as tall—suggesting a much different, warm temperate, ecosystem during the Eocene (Figure 1.18). The stumps are the largest and most easily visible fossils of the Florissant Formation (Evanoff and others, 2001). With names like "Big Stump," they do not disappoint at 12 ft (3.7 m) in diameter and up to 15 ft (4.6 m) tall. They are among the largest diameter ***in situ*** (still in place) fossil stumps in the world and include the world's only fossil redwood trio (Figure 1.19) (Meyer, 2003). Much smaller, more delicate and more abundant than the stumps are the fossils preserved in the sediments of ancient Lake Florissant. These lake sediments preserve one of the most diverse insect fossil localities on the planet with some 1,500 species of extraordinarily well preserved mayflies, dragonflies, cockroaches, bristletails, grasshoppers, earwigs, aphids, green lacewings, flies, bugs, beetles, wasps, ants, and butterflies (Meyer, 2003). The world's only known tsetse fly fossil is also found there and the wasp *Palaeovespa* serves as the park's logo (Figure 1.19). At least 150 species of plants, dominated by beech family (*Fagopsis*) and elm family (*Cedrelospermum*) are represented by flowers, fruits, seeds, and leaves. Flowers of *Florissantia*, a plant from the same family as cocoa and cola nuts are even found there. Fish, snails and other lake dwellers round out the fossils. Stream deposits of the Florissant Formation contain mammals such as the three-toed horse *Mesohippus*, brontotheres (also called titanotheres, giant herbivores of an extinct family), and a variety of rodents and rabbits (Lloyd and others, 2008). Florissant's paleoecosystem was composed of communities of animals and plants that today are found across the country or even around the world. Because of its outstanding preservation and diversity of fossil plants, and age near the "greenhouse"–"icehouse" climatic transition, the Florissant Formation is critical to understanding fossilization processes, and refining techniques used to reconstruct paleoecosystems and paleoelevation (Boyle and others, 2008; Leopold, 2008; Meyer, 2001, 2003; Meyer and Smith, 2008).

Agate Fossil Beds National Monument, Nebraska

The Fossil Hills rise over the treeless prairie of Agate Fossil Beds National Monument (authorized 1965) in northwestern Nebraska (Figure 1.20). The monument now has an average temperature of 45.8°F (7.7°C) and 14 in (36 cm) of precipitation. During the early Miocene, 19 million years ago, a drought on an arid savannah led to the deaths of perhaps thousands of 3 to 4 ft (about 1 m) tall ***Menoceras*** rhinoceros and dozens of the very bizarre chalicothere ***Moropus*** *elatus* that congregated at a watering hole (Figure 1.20). Similar scenarios play out today on the Serengeti of Africa. Scavengers such as the boar-like entelodont ***Daeodon*** (commonly called "*Dinohyus*") and bear dogs (such as

Daphoenodon) trampled and rummaged through the bone beds preying on the weakened animals and gnawing on the carcasses of those that already died (Figure 1.21). Raptors and scavenging birds also feasted on the carcasses (Chandler, 1998). The watering hole is now preserved as a bone bed, literally carpeted with hundreds of thousands of bone, in some areas there are nearly 10 bones in every square foot (more than 100 bones per square meter) (Hunt, 1990). The bone bed forms the base of the Anderson Ranch Formation (historically called the “upper Harrison beds”) (Hunt, 2002). So abundant and well preserved are the fossils here that they revolutionized paleontologists’ understanding of the early Miocene Epoch and were used as part of the original description and characterization of parts of the Arikareean North American land mammal age (Wood and others, 1941). Bear dog dens and burrows are also preserved just above the bone bed and are some of the oldest and largest vertebrate trace fossils in the world (Hunt, 1995; Hunt and others, 1993; Hunt and others, 1983).

Older fossils from the Harrison Formation, about 22-23 million years old, are preserved in windblown sands and ancient soil layers (paleosols). These layers include some of the largest trace fossils in the Cenozoic fossil parks, the nearly 7 ft (2 m) tall land-beaver burrows ***Daemonelix***—the devil’s corkscrew (Figure 1.21). Bear dog dens and burrows, just outside of the park, are up to 33 ft (10 m) long and from about 3 to 7 ft (1-2 m) in diameter making them the largest vertebrate burrows in the fossil record (Hunt, 1995; Hunt and others, 1993). The Stenomylus Quarry contains abundant, and in some cases nearly mummified, remains of the gazelle-like camel *Stenomylus*. Fossils of the three-toed horses *Parahippus* and *Kalobatippus* are also found in the park.

Hagerman Fossil Beds National Monument, Idaho

The world’s most abundant and diverse assemblage of Pliocene-aged mammals is preserved at Hagerman Fossil Beds NM (McDonald, 1993). The fossils are entombed within 600 ft (183 m) of rocks called the Glenns Ferry Formation deposited between about 3-4 million years ago, making them the youngest fossils in the Cenozoic fossil parks. The silts, muds, and sands and occasional volcanic ash and lava layers of the Glenns Ferry Formation represent river floodplain sediments, with a period of standing water (marsh or lake) in between (Ruez, 2006). A large lake of varying size and depth occupied the basin from between 8.5 and 2 million years ago (Link and others, 2002). More than 200 species of plants and animals are known from the lake and streams sediments of the Glenns Ferry Formation, deposited in and around ancient Lake Idaho, and now exposed in highly eroded bluffs along the Snake River (Figure 1.22) (McDonald and others, 1996). Ancient Lake Idaho and surrounding streams, floodplains, and nearshore ecosystems were home to a variety of fish, a number of birds, insectivores, rabbits, rodents, beavers, sloths, a coyote ancestor, bears, saber-toothed cats, mastodons, peccaries, camels, deer, and pronghorn—all preserved as fossils within Hagerman Fossil Beds NM. The most famous fossil, however, is also the state fossil of Idaho: the Hagerman Horse *Equus simplicidens*

(Figure 1.23). The park's 3.2 million-year-old Hagerman Horse Quarry yielded the largest sample of this species and is represented by fossils of at least 150 individuals, likely killed during a drought and buried during a subsequent flash flood (Richmond and McDonald, 1998). Most closely related to the modern Grevy's zebra, the Hagerman Horse is the oldest species in the modern horse genus ***Equus*** and the result of 50 million years of horse evolution preserved in the Cenozoic fossil parks (see Chapter 6). Today, the average temperature of the park is nearly 52°F (11°C) with rainfall of 10 in (25 cm). Fossils from the open pine forest—carpeted with grasses—ecosystems of the Glenns Ferry Formation suggest a similar mean annual temperature for this part of Idaho but perhaps twice the precipitation during the Pliocene (Ruez, 2006).

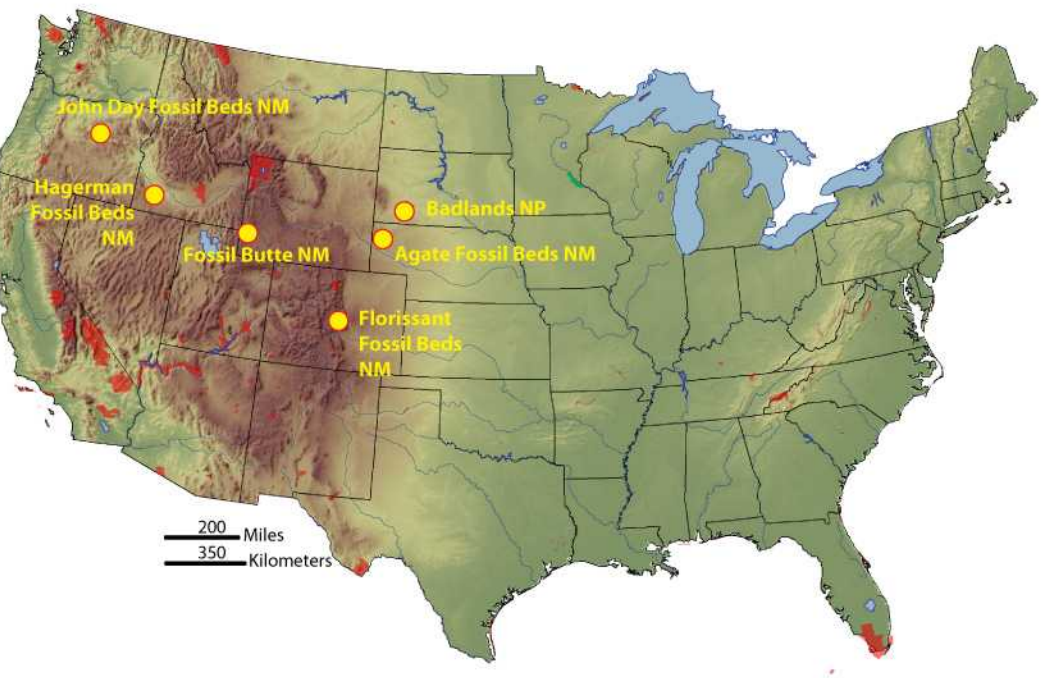
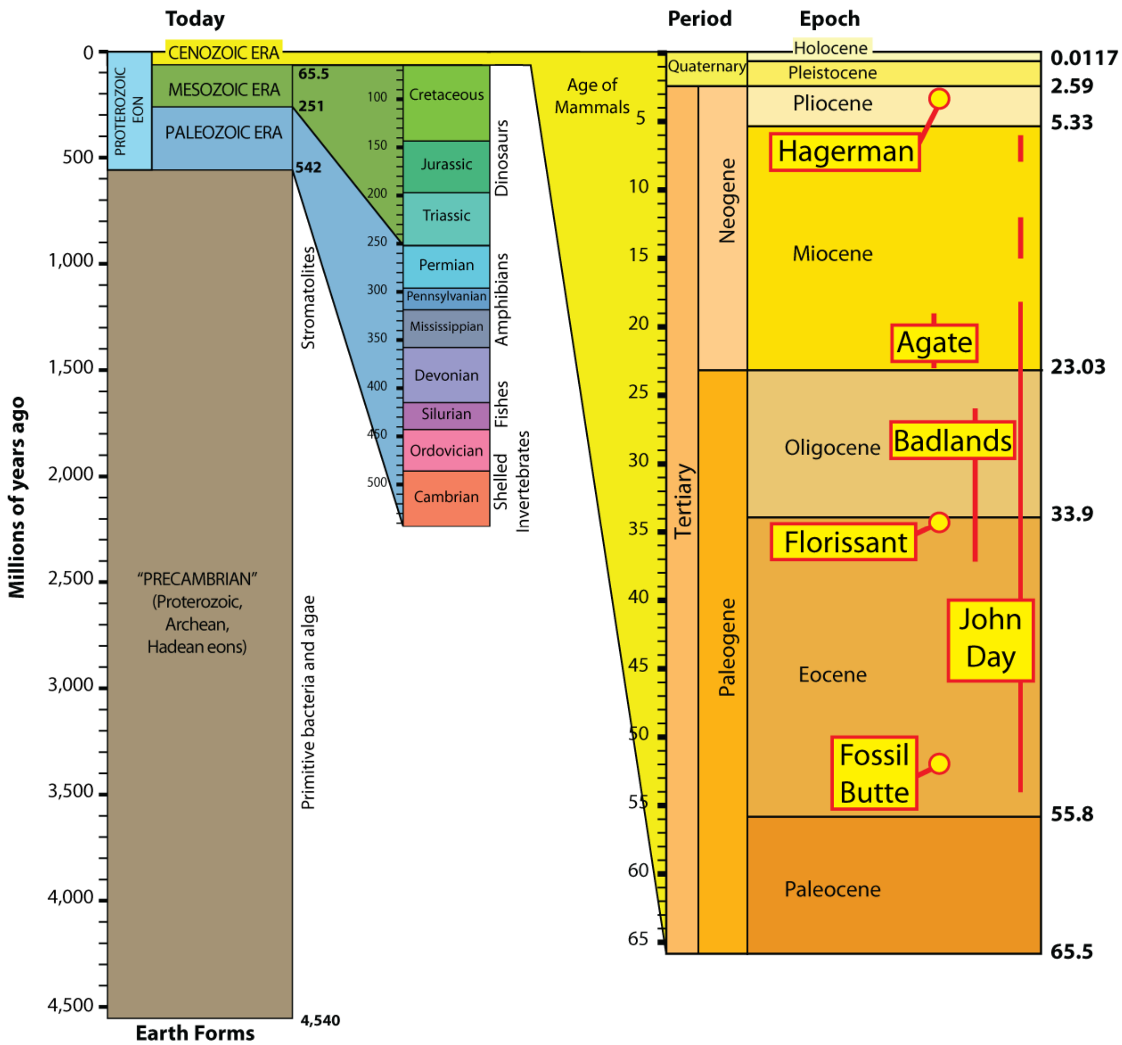


Figure 1.1. Location map for the six Cenozoic fossil parks. Red areas are other units of the National Park Service. NM = National Monument; NP = National Park. (Base map modified from Lillie [2005].)



<u>Figure 1.2</u>. The geologic time scale. The bar on the left shows the different **eons** of geologic time, with the Phanerozoic ("visible life") Eon divided into Paleozoic ("ancient life), Mesozoic ("middle life") and Cenozoic ("recent life") **eras**. The expanded bar in the middle shows the **periods** of the Paleozoic and Mesozoic eras. The expanded bar on the right shows the Paleogene and Neogene (together the "Tertiary") and Quaternary periods of the Cenozoic Era. These periods are in turn divided into smaller time intervals known as **epochs**. The time ranges represented by the Cenozoic fossil parks are indicated with the red bars and yellow dots. Note that the "Precambrian" (an informal term encompassing the Hadean, Archean, and Proterozoic eons) covers some 87% of Earth's 4,540 million year history! The Paleogene and Neogene periods together span only 63.7 million years (about 1.4% of Earth's history). The geologic time scale used here is based on information from the U.S. Geological Survey (USGS, 2007) and the International Commission on Stratigraphy (2009). The colors are those suggested by USGS for use on geologic maps to designate units of the particular time intervals.

Digging Deeper Box 1.1. Rock name in-formation

Throughout this manual rock layers in the Cenozoic fossil parks will be referred to by their geologic names: for example, Green River Formation; Columbia River Basalt Group; Glenns Ferry Formation; Chadron Formation; Turtle Cove Member. What do these names mean?

Geologists divided up geologic time into named intervals—eons, eras, epochs, periods—to create the standard geologic time scale (Figure 1.2). In the same manner, geologists organize rock layers with similar composition, age, or fossils into named units called "formations." The different formations in a park are a readily-identifiable tangible for visitors, especially when more than one are viewable at a particular vantage point (Figure 1.9). Visitors don't necessarily need to know the various formation names, but it does provide a handy way to refer to different rock layers during programs.

Formations are always named after a geographic place where they are particularly well-represented. For example, the Chadron Formation was named for rocks found near the town of Chadron, Nebraska. Formations can be further subdivided into "members." At Badlands NP, the Chadron Formation is divided in the Ahearn, Crazy Johnson, and Peanut Peak members. On the other hand, formations can also be grouped together into "groups." The Chadron Formation is part of the White River Group, along with the Brule Formation and Sharps Formation.

Thus the formation names provide a classification system for rock layers in the park and allow comparisons between different formations within and between parks. Geologists don't always agree on exactly which formation or group rocks should be assigned to. Over time different interpretations of the geology can lead to formations being renamed or reassigned.

Some previously named formations contain a wide variety of different rocks and fossils that are in need of further study for further refine and define individual formations. In these instances they may be referred to as "assemblages." For example, communities of fossils from paleoecosystems of the Clarno, Mascall, and Rattlesnake rocks are called the Clarno, Mascall, and Rattlesnake assemblages.

For detailed geologic information and brief histories of formation names, refer to the U.S. Geological Survey's "GEOLEX" (Geologic Names Lexicon) website: http://ngmdb.usgs.gov/Geolex/geolex_home.html.

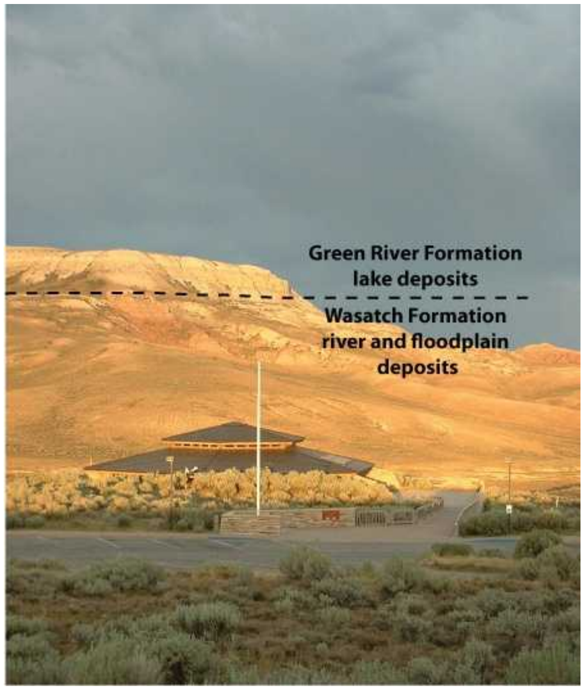


Figure 1.3. The oldest paleoecosystems at Fossil Butte NM are preserved within the more than 52 million-year-old Wasatch Formation and Green River Formation. In this photo, Fossil Butte looms over the park's visitor center with the multicolored Wasatch Formation below the tan-colored Green River Formation (Photo by Jason Kenworthy.)

Figure 1.4. *Knightia eocaena* is perhaps the most abundant articulated vertebrate fossil in the world! It is also the state fossil of Wyoming and the most common fossil fish found at Fossil Butte. In some layers mass mortalities of fish (such as this slab) indicate the schooling nature of the fish and suggest a catastrophic event in the lake. The fish are each about 4 in. (10 cm) long. (NPS Photo.)

Figure 1.5. The Clarno palisades (left) of John Day Fossil Beds NM preserve 44 million-year-old fossils of the Clarno Nut Beds (right), a near tropical forest with palm trees and bananas (Palisades photo by Jason Kenworthy; Clarno Nut Beds mural by Larry Felder for NPS, photographed by Will Landon for NPS.)

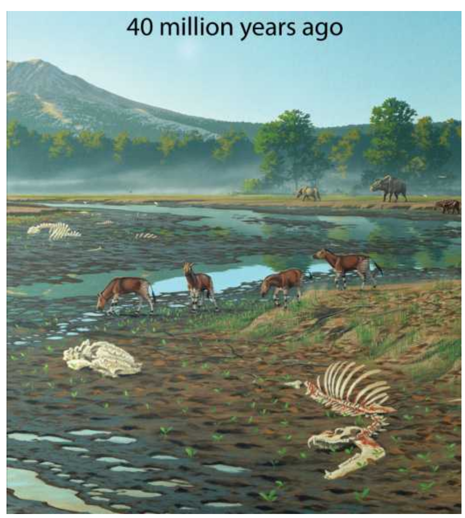


Figure 1.6. The Clarno palisades (Figure 1.5) also contain 40 million-year-old fossils similar to those excavated from the Hancock Mammal Quarry. An amynodont (rhino-like mammal) skeleton is in foreground, four-toed *Epihippus* horses are in the center of the image. Large brontotheres stand in the background. (Mural by Roger Witter for NPS; photographed by Will Landon for NPS.)

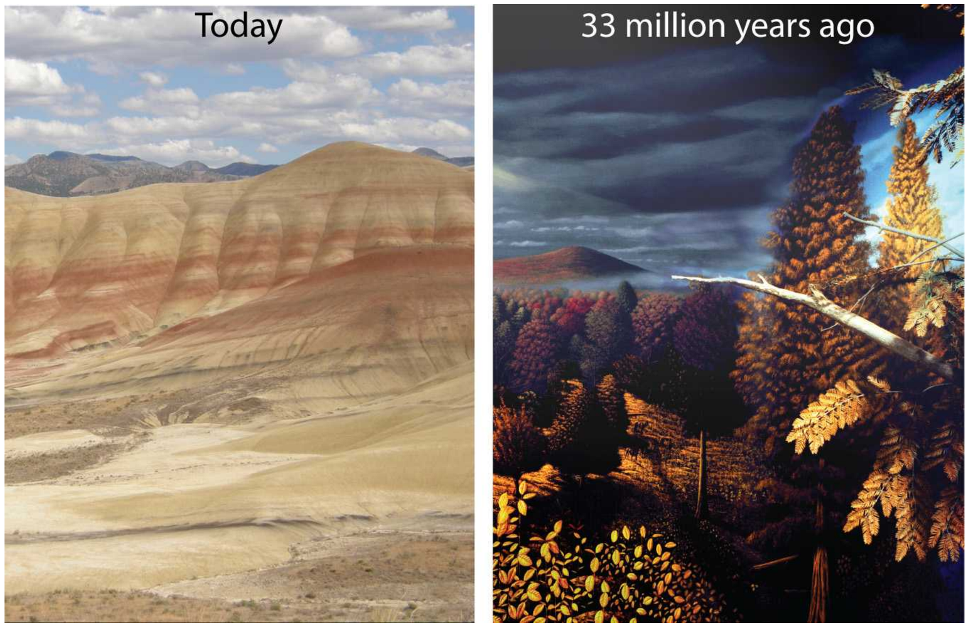


Figure 1.7. The Painted Hills unit of John Day Fossil Beds NM contains vibrant red, yellow, and black paleosols. The plant fossils of the Bridge Creek Flora at the Painted Hills unit suggest a temperate hardwood forest like those of the southeastern United States or central China. (Painted Hills photo by Jason Kenworthy; Bridge Creek Flora mural by Larry Felder for NPS, photographed by Will Landon for NPS.)

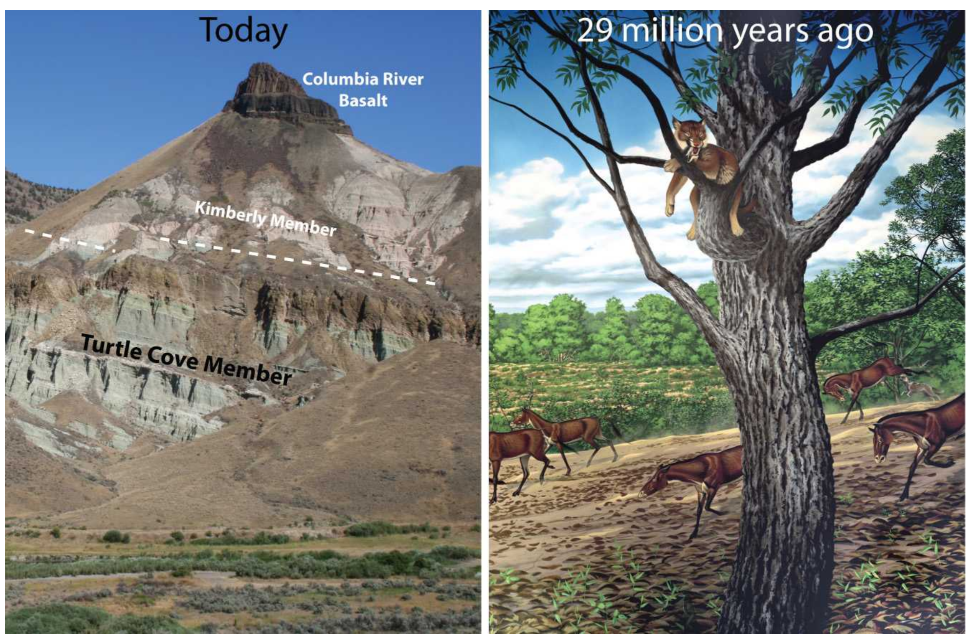


Figure 1.8. Greens and blues characterize the Turtle Cove Member found at the base of Sheep Rock in John Day Fossil Beds NM. The very fossiliferous Turtle Cove contains a large diversity of carnivores (such as the cat-like nimravid in the tree) as well as three-toed horses (*Mesohippus* and *Miohippus*). (Sheep Rock photo by Robert J. Lillie; Turtle Cove Member mural by Roger Witter for NPS, photographed by Will Landon for NPS.)

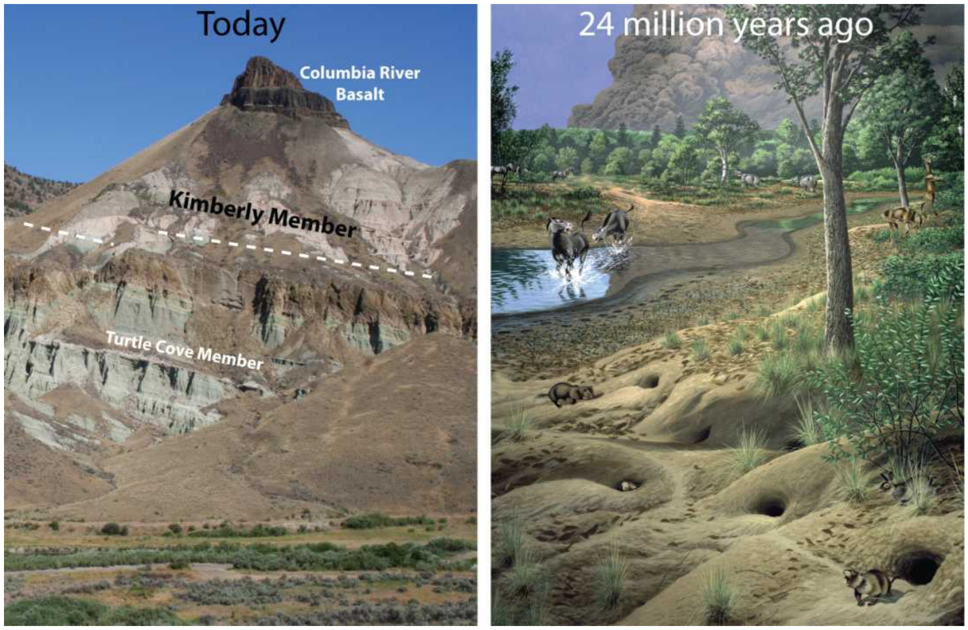


Figure 1.9. The pinks and tans of the Kimberly Member are about 27 to 24 million years old and found near the top of Sheep Rock in John Day Fossil Beds NM. The large browsing horse *Kalobatippus* runs across a stream. As seen in this image, burrowing animals are characteristic of the Kimberly Member. (Sheep Rock photo by Robert J. Lillie; Kimberly Member mural by Roger Witter for NPS, photographed by Will Landon for NPS).

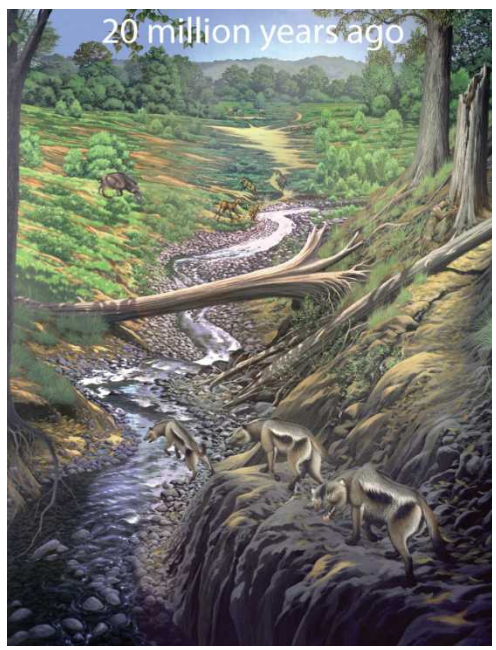


Figure 1.10. The “Haystack Valley” assemblages of John Day Fossil Beds NM suggest paleoecosystems such as desert scrubland and woodland. Bear dogs are illustrated in the foreground. (Haystack Valley mural by Roger Witter for NPS, photographed by Will Landon for NPS.)

Figure 1.11. Massive floods of basalts erupted from huge fissures in central and northeast Oregon 16 million years ago. The layers of Picture Gorge at the southern entrance to John Day Fossil Beds NM are evidence of dozens of these flows (Photo by Robert J. Lillie.)

Figure 1.12. Forests and lakes surrounded by savannah-like grasslands were found in central Oregon from 16 until about 12 million years ago. The mural shows three-toed browsing horses near the center while on the left, one of the earliest North American elephant relatives reaches with its trunk. These are paleoecosystems of the Mascall Formation of John Day Fossil Beds NM. View is from Mascall Overlook. (Mascall photo by Jason Kenworthy; Mascall Assemblage mural by Roger Witter for NPS, photographed by Will Landon for NPS.)

Figure 1.13. The youngest rocks in John Day Fossil Beds NM are those of the Rattlesnake Formation. Fossils and paleosols from the Rattlesnake suggest a true grassland environment for central Oregon 7 million years ago. The bear *Indarctos* is portrayed in the foreground, while grazing horses flee the massive volcanic eruption. The caprock visible in the photo from the Mascall Overlook was formed during that volcanic explosion. (Rattlesnake outcrop photo by Jason Kenworthy; Rattlesnake Assemblage mural by Roger Witter for NPS, photographed by Will Landon for NPS.)

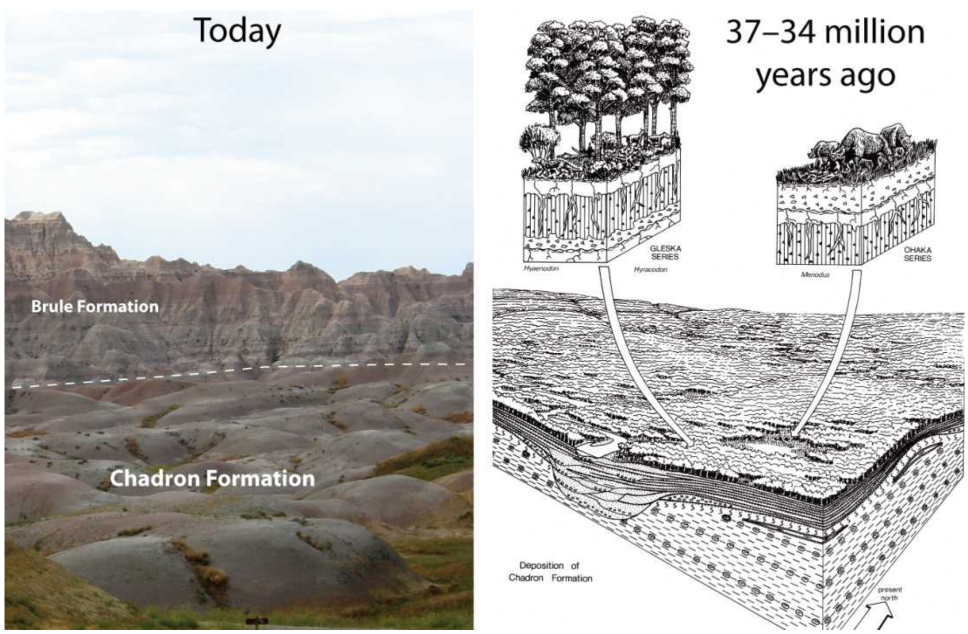


Figure 1.14. The low, rounded gray hills of the Chadron Formation in Badlands NP are not vegetated now. Between 37 and 34 million years ago however, the region was covered by a nearly tropical forest! Huge titanotheres lived near these forests or in open disturbed areas. Photo taken near Yellow Mounds Overlook. (Photo by Jason Kenworthy; paleosol reconstruction from Retallack [1983] reproduced with permission of Gregory Retallack and the Geological Society of America).

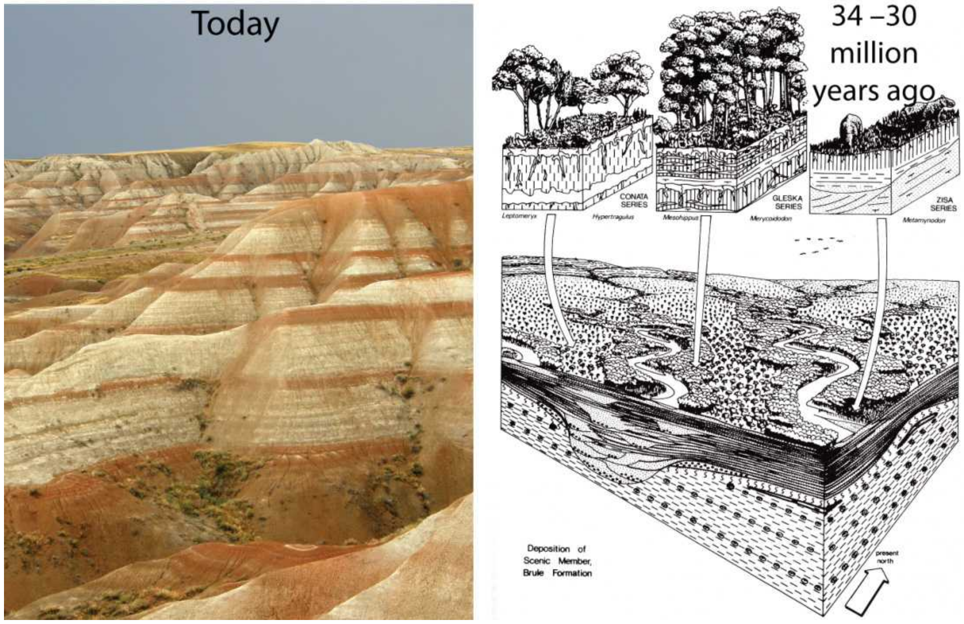


Figure 1.15. The Brule Formation of Badlands NP contains the world's richest record of Oligocene life. From 34 to 30 million years ago oreodonts (*Merycoidodon*) and turtles were prominent components of the ecosystem. The red and grey bands are paleosols (ancient soil layers) that are particularly visible after a rain as in this photo from the Bigfoot Pass Overlook (Photo by Jason Kenworthy; paleosol reconstruction from Retallack [1983] reproduced with permission of Gregory Retallack and the Geological Society of America).

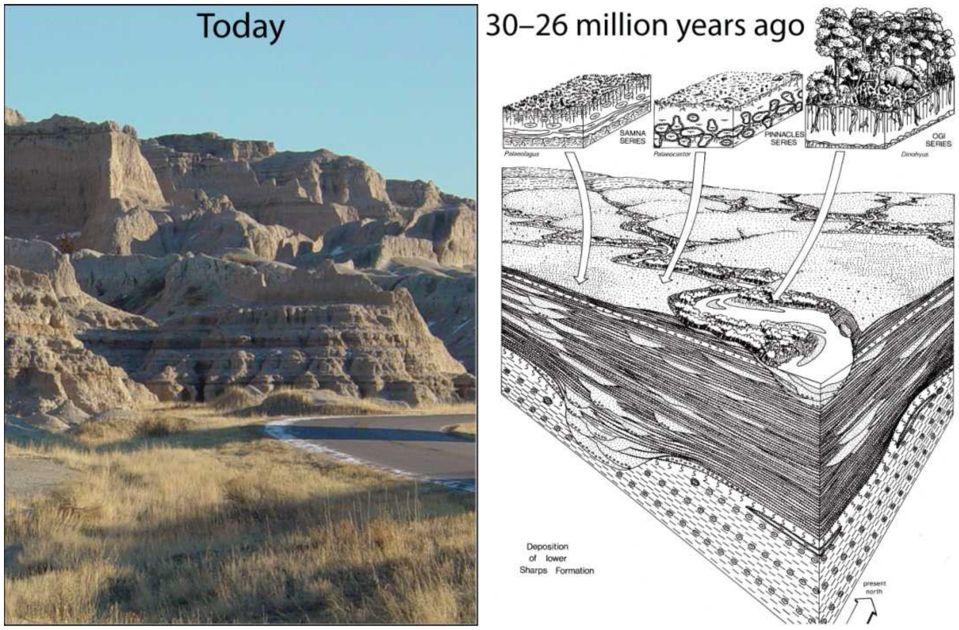


Figure 1.16. The Sharps Formation makes up the highest pinnacles in Badlands NP. Paleosols record a savannah or steppe-like ecosystem from 30 to about 26 million years ago, very different from the nearly tropical forests found in the Chadron Formation (Figure 1.14). The base of the Sharps Formation is a thick white volcanic ash layer called the Rockyford Ash. (NPS photo courtesy of Rachel Benton [Badlands NP]; paleosol reconstruction from Retallack [1983] reproduced with permission of Gregory Retallack and the Geological Society of America.)

Digging Deeper Box 1.2. Badlands National Park also interprets fossils from the Age of Dinosaurs

The Cenozoic fossil parks were primarily established for their fossils after the dinosaurs went extinct. However, Badlands NP also contains a record of life from the end of the Mesozoic Era 74 to 65.5 million years ago (the later part of the Cretaceous Period). During this time, the park (and most of west-central North America) was flooded by the Cretaceous Interior Seaway that stretched from today's Gulf of Mexico to the Arctic Ocean. Large fearsome marine reptiles (mosasaurs), cepahlopods (same **class** as squid and octopus) with coiled shells called ammonites, and sea turtles the size of Volkswagen Beetles flourished in this tropical inland sea. Their fossils are found in rocks of the Pierre Shale and Fox Hills Formation. The striking Yellow Mounds mark a long time of exposure to the elements and consequent soil formation on the Pierre Shale before the emergence of Cenozoic paleoecosystems (Figures 1.14–1.16). Interpreting the paleoecosystems of this topical time reinforces the cooling and drying evident in the younger Cenozoic ecosystems.

Separating the Age of Dinosaurs from the Age of Mammals is the "K-T" (for Cretaceous-Tertiary) boundary 65.5 million years ago. One of the five most deadly extinction events of the past 542 million years marks this boundary (Box 1.3). Badlands NP is the only Cenozoic fossil park that commonly interprets fossils from both the Mesozoic and Cenozoic eras, offering an opportunity to connect visitors to this extinction event that is a part of popular culture.

***Digging Deeper Box 1.3*. Mass extinction ushers in the "Age of Mammals"**

There have been five major mass extinctions over the past 542 million years (Raup and Sepkoski, 1982). The extinction at the "K-T" boundary ("K" = Cretaceous, "T" = Tertiary) 65.5 million years ago is probably the one most familiar to visitors as it heralded the end of the Age of Dinosaurs and ushered in the Age of Mammals. It was not the most severe of the five. In fact it ranks fifth as far as taxonomic diversity lost in both the oceans (15% of marine invertebrate families went extinct) and on land (about 6% of terrestrial families) (Benton, 1995).

Although the K-T extinction ranks fifth in loss of diversity, for mammals it was not necessarily *how much* was lost, but *what* was lost that made the difference. The collapse of ecosystems that were dominated for nearly 150 million years by terrestrial dinosaurs and marine reptiles (like Badlands NP's mosasaurs) opened up countless vertebrate niches that mammals exploited during the Cenozoic Era. Because of this complete collapse of ecosystems that were dominated by dinosaurs and marine reptiles, and their replacement by mammal-dominated ecosystems, McGhee and others (2004) suggest that the K-T extinction was second only to the end-Permian extinction event in terms of "ecological severity."

The end-Permian mass extinction 251 million years ago holds the dubious distinction as the largest mass extinction event in the fossil record. Around *half* of marine invertebrate families and more than *sixty percent* of terrestrial families went extinct at the end of the Permian (Benton, 1995; Sepkoski, 1982 as summarized by McGhee and others, 2004). Overall loss of species may have totaled an astounding 96% in the oceans and 70% to 80% on land!

What was the cause of the K-T extinction? Many visitors will share that an "asteroid (or comet) killed the dinosaurs." It is true that a large space rock crashed into the Yucatan Peninsula, near Chicxulub, Mexico 65.5 million years ago. But like most things in the natural world, there were probably other contributors. The end of the Cretaceous Period was also marked by a dramatic drop in sea level, which greatly reduced marine productivity. In addition, vast eruptions of basalt—much larger than those of the Columbia River Basalts exposed at John Day Fossil Beds NM—were disgorged on to the Earth's surface during the Late Cretaceous. They are now preserved as the Deccan Traps Flood Basalt in India. Some paleontologists believe that dinosaur diversity was already on the decline long before an asteroid impact. The combination of these events, punctuated by a massive extraterrestrial impact marked the end of the Age of Dinosaurs. A recent publication in the journal *Science* by Schulte and others (2010) describes the role of the Chicxulub asteroid as the mass extinction trigger. The discussion by Prothero (2006) downplays the role of the impact.

Figure 1.17. Dr. Hiram Prout, a St. Louis dentist, described this titanothere jaw in 1846 (Prout called it a "Palaeotherium"). It was the first scientifically described fossil specimen from the American West and was unearthed from the Chadron Formation of what is now Badlands NP. The jaw is currently in the collections of the Smithsonian Institution's National Museum of Natural History in Washington, D.C. (Photo by Vincent Santucci [George Washington Memorial Parkway].)

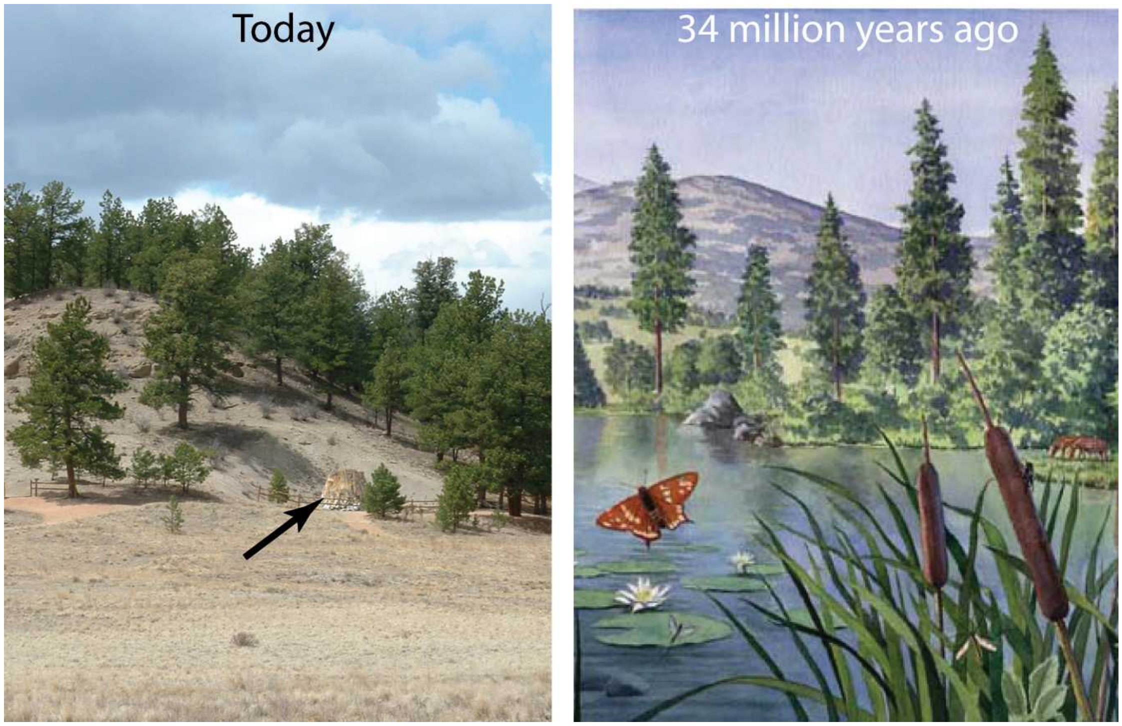


Figure 1.18. The ponderosa pine forest of Florissant Fossil Beds (left) is growing atop fossil evidence of a forest with much larger *Sequoia*-like trees that were buried by a volcanic mud flow 34 million years ago (see "Big Stump", arrow in center of photo). Also preserved in the park are delicate fossils from a lake ecosystem (right). Although the conical landforms look similar in the mural and the photo, the mural depicts a large, looming volcano (now eroded away) miles south of the park. The much smaller feature in the photo is a small hill (Photo by Jason Kenworthy; Image of NPS mural courtesy Jeff Wolin [Florissant Fossil Beds NM].)

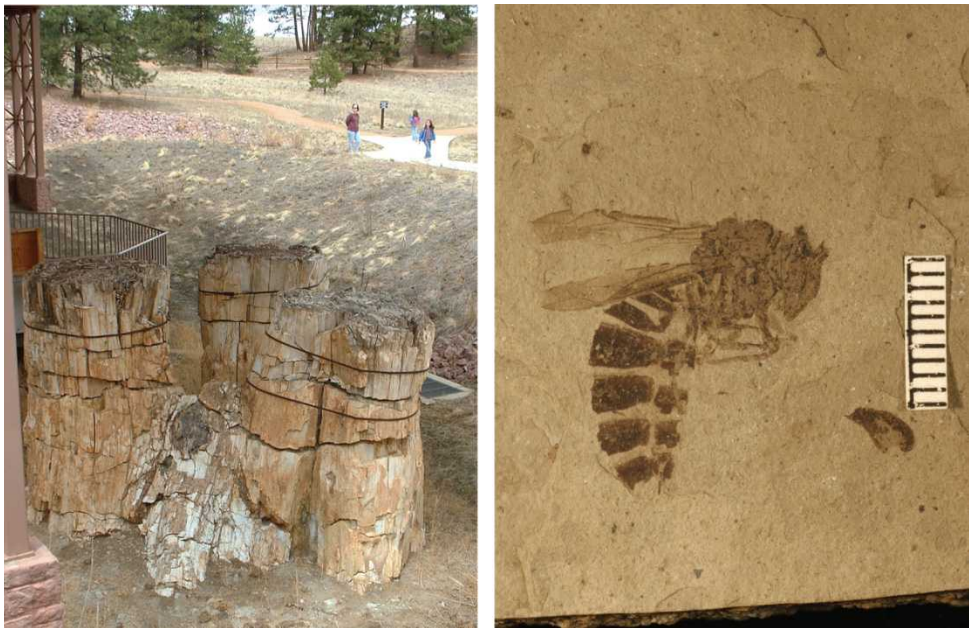


Figure 1.19. Florissant Fossil Beds NM preserves fossils big and small. The petrified “trio” of *Sequoia*-like trees (left) is the only such trio known in the fossil record—anywhere. These trees were more than three times as tall as the ponderosa pines in the background; their fossil stumps are about 15 ft (4.6 m) tall. The park also contains one of the world’s most diverse and well-preserved collection of insect fossils, which are found in lake deposits. *Palaeovespa* (right) is a fossil wasp and serves as the park’s logo. Note the fine detail, even on the wings (scale bar increments are in millimeters!) (Trio photo by Jason Kenworthy; *Palaeovespa* NPS photo.)

Figure 1.20. The Fossil Hills (University Hill on the left and Carnegie Hill on the right) at Agate Fossil Beds NM (left) preserve an amazing fossil bone bed, recreated in the diorama and mural (right) in the visitor center. The mural depicts the scene of hundreds or thousands of sheep-sized rhinoceros (lower right of mural and bone bed in diorama) and giraffe-shaped *Moropus* (center of mural and mounted skeleton in diorama). These animals died at a watering hole during a drought on Nebraska's semi-arid savannah 19 million years ago (Fossil Hills photo by Jason Kenworthy; NPS photo of diorama and mural.)

Figure 1.21. Fearsome scavengers and the devil's corkscrew at Agate Fossil Beds NM. The nearly 6 ft (2 m) tall entelodont *Daeodon* (commonly called *"Dinohyus"*) scavenged the plentiful carcasses of the watering hole (Figure 1.20) (left). These are the biggest and last of the entelodonts, which are also found at John Day Fossil Beds NM. *Daemonelix*—the devil's corkscrew—are burrows of terrestrial beavers called *Palaeocastor*, that are nearly 23 million years old. For scale, this enclosure along the *Daemonelix* Trail is nearly the size of a telephone booth (NPS photo of diorama and mural; *Daemonelix* photo by Jason Kenworthy.)

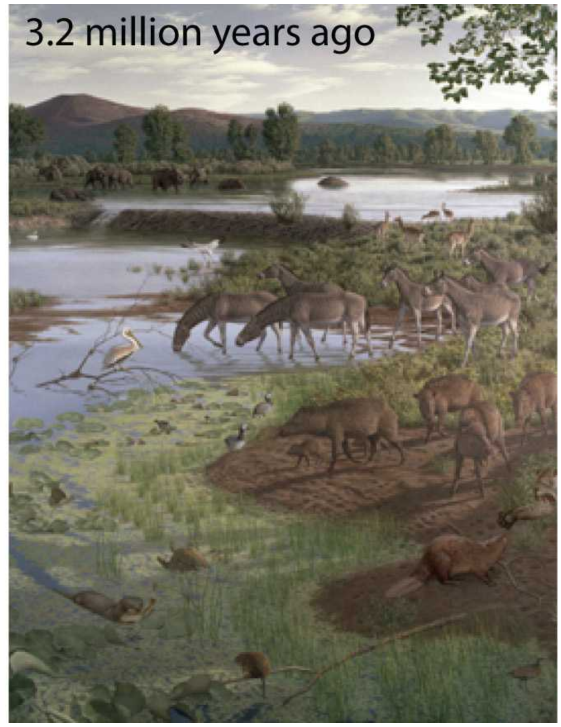


Figure 1.22. The slopes of Hagerman Fossil Beds NM preserve the world's most diverse Pliocene-aged fossil assemblage with more than 220 species of plants and animals. The photo on the left shows, however, that the fossil layers are also susceptible to huge landslides (this is a 2008 photo of a 1987 slide that wiped out an irrigation pumping station along the Snake River). The mural on the right depicts the river or lakeside environment interpreted for some layers in the park. Hagerman Horses are in the center of the mural (Photo by Jason Kenworthy; Mural by Jay Matternes, copyright by the Smithsonian Institution. Used with permission.)

Figure 1.23. The 3.2 million-year-old Hagerman Horse is the oldest member of the modern horse genus *Equus*. A true hoofed grazer the size of a zebra, the Hagerman Horse is very different from the oldest fossil horse known in the Cenozoic fossil parks: the 52 million-year-old "*Hyracotherium*" from Fossil Butte NM. See Chapter 6 for more on horse fossils from each of the Cenozoic fossil parks (NPS photo by Phil Gensler [Hagerman Fossil Beds NM].)

Chapter 2

Interpretation connects visitors to the Cenozoic fossil parks

Interpretation is the "cohesive development of a relevant idea that creates opportunities for visitors to form their own intellectual and emotional connections to the meanings inherent in a park resource" (National Park Service, 2008). It goes beyond summarizing interesting facts about the park. Cenozoic fossil park interpretation opens possibilities for visitors to link between the past, present, and future. Interpretation can instill a sense of stewardship leading to respect and responsible behavior toward non-renewable fossils and other park resources (Beck and Cable, 2002). This manual aims to provide interpreters with a foundation of resource knowledge and interpretive ideas so that they may share the common stories of evolving ecosystems told by the six Cenozoic fossil parks.

This chapter begins with a brief introduction to National Park Service (NPS) interpretive theory through Tilden's Six Principles and the NPS Interpretive Development Program's Interpretive Equation. It then separates components of the interpretive equation as they apply to paleontology interpretation. Interpretive themes from the Cenozoic fossil parks are summarized and additional themes that correspond to the concept of Cenozoic climate change and ecosystem evolution are suggested by the author.

Tilden's Six Principles of Interpretation

In 1957 Freeman Tilden, one of the "elders" of NPS interpretation, formulated six principles central to all interpretation in his classic book *Interpreting our Heritage* (Tilden, 1977).

1. Any interpretation that does not somehow relate what is being displayed or being described to something within the personality or experience of the visitor will be sterile.

2. Information, as such, is not interpretation. Interpretation is revelation based upon information.

3. Interpretation is an art, which combines many arts, whether the materials presented are scientific, historical, or architectural. Any art is to some degree teachable.

4. The chief aim of interpretation is not instruction, but provocation.

5. Interpretation should aim to present a whole rather than a part, and must address itself to the whole man rather than any phase.

6. Interpretation addressed to children should not be dilution of the presentation to adults, but should follow a fundamentally different approach.

Tilden's principles continue to serve today as the backbone of interpretive efforts and techniques outlined by various authors and incorporated into the mission of the National Association for Interpretation (Beck and Cable, 2002; Brochu and Merriman, 2002; Ham, 1992; Larsen, 2003).

Various aspects of this manual fit one or more of Tilden's principles. Linking the Cenozoic fossil parks via a shared story of climate change is an example of presenting "a whole" story (Principle 5). Contrasting the long-term cooling and drying of Earth's climate over *tens of millions* of years with the rapid warming over the past *tens* of years may provide a revelation to some visitors (Principle 2) and provoke action from others (Principle 4). Any interpreter working at a fossil park has seen the bright-eyed child burst through the doors of the visitor center and gaze in wonder at the sometimes strange fossils on display. Given this common intangible link with younger visitors, interpretation to children is equally important (Principle 6) and can lead to further interpretation with the rest of the family. Having the family share experiences of trips to other fossil parks, and perhaps having the children act like their favorite fossil animal (Principle 3), is a way to relate to their personal experiences (Principle 1).

The Interpretive Equation

The NPS Interpretive Development Program (IDP) (2008) uses an equation to help visualize how information is conveyed to park visitors:

(KR + KA) x AT = IO

KR = Knowledge of the Resource

KA = Knowledge of the Audience

AT = Appropriate Technique

IO = Interpretive Opportunity

According to the equation, interpretive opportunities are enhanced when an interpreter has a good content base of resource knowledge; understands the audience's background, education, and priorities; and uses interpretive techniques appropriate for that audience. A complementary method to visualize the meaning behind the interpretive equation is the "PAIRing" method presented in Box 2.1 and Figure 2.1 (Mathis, 2009). The next section provides some information on how interpreters at the Cenozoic fossil parks can incorporate knowledge of the resource, knowledge of the audience, and appropriate technique into paleontology interpretation.

Knowledge of the Resource: Foundation of Interpretation

Resource knowledge is the foundation of all interpretation. It is the facts, figures, and other tangibles that provide substance for an interpretive program or informal contact. Chapters 1, 4, 5, and 6 present some resource information for all six Cenozoic fossil parks and a synthesis of how ecosystems evolved during the Cenozoic. Chapter 7 presents resource information regarding modern climate change.

Knowledge of the Audience: Background, Experiences, and Interests

Developing interpretive opportunities requires knowledge of a park's typical audience, and a program's specific audience. There are a number of sources for this information. Visitor surveys provide information on demographics, expectations, facility utilization and rankings of park programs and facilities. More detailed social science analyses summarize information gleaned from such surveys and include in-depth observation and analysis of the visitors' ethics, understanding and appreciation of the park, and the effectiveness of interpretation in increasing understanding and appreciation. The Park Studies Unit at the University of Idaho has conducted visitor surveys through the Visitor Services Project for Agate Fossil Beds NM (Holmes and others, 2008), Badlands NP (Simmons and Gramann, 2001), and John Day Fossil Beds NM (Le and others, 2005). These surveys are above and beyond the annual Visitor Survey Card program which focuses on utilization and quality of park resources and services. As of April 2010, Visitor Services Project surveys have not yet been conducted for Florissant Fossil Beds NM or Hagerman Fossil Beds NM. A detailed social science study was conducted for the Fossil Butte NM visitor center (Hockett and Roggenbuck, 2002) and interpretive quarry (Hockett and Roggenbuck, 2003).

As reported in the above surveys, the majority of Cenozoic fossil park visitors are first-time visitors from the park's home or immediately adjacent states. Most stop at park visitor centers and the adults tend to be highly educated (more than half have college undergraduate or higher degrees). They also have a strong interest in fossils with more than half (52%) of Fossil Butte visitors reporting "quite a lot" or a "strong" interest in fossils. Learning about fossils was considered the "favorite hobby" of 2.2% of Fossil Butte visitors (Hockett and Roggenbuck, 2002). Visitors to the Cenozoic fossil parks, and indeed all NPS sites, share one commonality: they are in an informal learning setting and are generally part of a noncaptive audience. Their motivation to visit a Cenozoic fossil park derives, in part, from their interest in fossils. Given the remote location of the Cenozoic fossil parks, most visitors have made a significant effort to just get to the visitor center! The efforts of interpreters to engage visitors should utilize the visitors' self-identified interest in fossils to create opportunities for personal discovery.

Appropriate Technique 1: Making a "Whole" by Interpreting Beyond Park Boundaries

One of the main goals of this manual is to provide suggestions to assist interpreters in integrating their park's fossils into the larger context of global climate change over long time spans. This information can be made more whole (Tilden's fifth principle) by considering parts of the story told by different parks. Consider, for example, that individual Civil War parks such as Antietam

National Battlefield (Maryland) or Gettysburg National Military Park (Pennsylvania) interpret not just the significance of the battles fought there, but also how those battles were the result of previous engagements and how they influenced future operations. The Cenozoic fossil parks each illustrate a significant part of the story of global cooling and drying spanning the past 65 million years. The story of changing climate and evolving ecosystems is common to all six parks. Visitors who have travelled from other parts of the world, country, or state to get to a given park have experienced many different ecosystems. Interpretation at each of the parks can extend a visitor's appreciation of the different landscapes, climates, plants, and animals they have just experienced. Fossil park interpretation can help visitors appreciate not only how these things change from one place to another today, but also how they have changed over time.

Many parts of the whole story are recorded by fossils discovered outside of the Cenozoic fossil parks. John Day Fossil Beds NM, for example, interprets fossils from more than 700 localities distributed over more than 10,000 square miles (26,000 square kilometers), while the park itself contains only a fraction of those localities within just 22 square miles (57 square kilometers) of NPS land. Likewise, Fossil Butte NM interprets a 52-million-year-old subtropical lake. A small proportion of the sedimentary and fossil record of the lake is preserved within park boundaries, and that was primarily under the lake's deepest part. Rocks and fossils from the near-shore environments are preserved outside of the park. Because the fossil record does not stop at park boundaries, interpretation of stories from "beyond the fence" thus provides context and connections for fossils within each park.

<u>Appropriate Technique 2: Interpreting "Controversial" Topics</u>

The manual discusses three topics that may be controversial in the eyes of some visitors: age of the Earth, evolution, and climate change. These topics are relevant to fossil park interpretation and are not considered controversial by scientists. Visitors may at times challenge interpreters on these issues. It is true that scientists continue to research and debate differing ideas on the *details* of evolutionary processes as well as on the factors affecting climate change and their relative contributions. But it is well established that Earth is more than 4.5 billion years old (Newman, 1997), that life forms have evolved over time (Scott, 2004), and that human activities *very likely* (>90% certainty) impact global climate (Le Treut and others, 2007).

Through its management policies and director's orders, the National Park Service requires that interpretation is based upon sound, peer-reviewed, and up-to-date science and does not require equal time for alternative, non-scientific explanations. Interpretation encourages the visitor to make their own connections to the meanings inherent in the resources. Interpreters need to respect that some visitors may not agree with an old Earth, evolution, or **anthropogenic** (resulting from the influence of humans) climate change. By putting on an NPS uniform, an interpreter has accepted the responsibility to present interpretation based on sound science involving observations and critical analysis of our planet. Interpretation of the various scientific methods regarding geologic dating techniques, the study of evolution, and ways to model past, current, or future climate change provides an insight into how science works. These topics should not be presented in ways that might suggest that scientists still have serious disagreements about Earth being old, life evolving, or humans affecting climate.

Science is a method of explaining forms and processes through observations of the natural world (Scott, 2004). One of the main issues raised by visitors questioning evolution is use of the word **theory**. For some people, the common-language use of "theory" suggests an idea, guess, or even a hunch, as shown in Box 2.2. For scientists the term "theory" is defined as "a well-substantiated explanation of some aspect of the natural world that can incorporate facts, laws, inferences, and tested hypotheses" (National Academy of Sciences, 1998). It is thus a very strong term—far more than an educated guess or hunch. Yes, evolution by natural selection is a theory, but it is not *just a theory*! Scientific theories are built from a foundation of scientific **facts.** Facts are confirmed observations and frequently result from direct measurement. Facts can change based on new data, observations, or measuring techniques.

If an audience mostly opposes the scientific position, interpreters should establish some common ground, or simply agree to disagree. It is not the job of the interpreter to change visitors' minds! Even if visitors do not accept the millions-of-years-old ages of the fossils, the Cenozoic fossil parks contain some of the most well-preserved, diverse and abundant fossils of the Cenozoic Era of geologic history. The sequence of events is still the same, and the overall story can still be shared. Scientists have researched them for decades and the parks are some of the best places on Earth to study them. Interpreters can strive to help *everyone* find their connection with the resource. If someone does not accept the scientific view, they can still leave with a sense of uniqueness for the park. Interpreters help foster such opportunities. The fossil tangibles do not change but the emotional and intellectual connections can certainly vary from visitor to visitor.

Appropriate Technique 3: Themes link tangibles and intangibles

Interpreters use theme statements to connect visitors with the tangible park resources and the intangible meanings inherent in the resources. Themes guide interpretive opportunities and should answer the "So what?" question. Tangibles provide the information essential to effective interpretation. Visitors can experience tangibles using one or more of their senses: sight, touch, hearing, or even taste (fossil bone sticks to inquisitive tongues!) and smell. Common tangibles at a fossil park include the actual fossils; rock layers (sedimentary **strata**); modern landscape; and visitor center exhibits, displays, or dioramas. Interpreters can help visitors notice additional tangible resources in the park as well. For example, interpreters on a nature hike may challenge visitors to observe the landscape in a new way in order to see the mule deer hiding in the brush. Likewise, at fossil parks, interpreters can provide visitors with a new way to look at the rock layers. First-time visitors to Agate Fossil Beds NM stand in the historic quarries and wonder "Where are all the fossils?" An interpreter may help them notice one tooth or bone fragment on the ground. Visitors' eyes can adjust and notice, with great excitement, that there are fossil fragments literally carpeting the quarry floor (Figure 2.2)! Additional ideas for tangibles are the distance travelled to get to the park (Chapter 3), or even the experience of the modern climate of the park.

Intangibles are the meanings inherent in tangible park resources. Connecting tangibles to intangibles elevates the dissemination of information to the level of true interpretation (Tilden's Principle 2). Finding intangibles for a fossil park may be more challenging than observing tangibles. Deep geologic time, fossilization processes, geologic processes (erosion, deposition, uplift of mountains, plate tectonics), ancient climates, and paleoecosystems are all potential intangibles (Chapters 3, 4, 5, and 6).

As important as these intangibles are as scientific concepts, they may not resonate with some visitors because they are not universal concepts. Universal concepts are intangibles that everyone can relate to. They include ideas such as home, change, life, death, family, beauty, awe, etc. Interpretation of the changes in paleoecosystems (landscapes, climates, and life) may provide the opportunity for incorporation of universal concepts. Change, adaptation, moving (migration), and death (extinction) are examples of universal concepts that can be applied to interpretation of fossils and climate change. Most universal concepts revolve around the idea of "self" and shared human experiences. There are no fossils of Cenozoic-aged hominids found within the Cenozoic fossil parks. However, the Pliocene-aged (3.2 million years old) fossils of Hagerman Fossil Beds NM are the same age as some of the earliest hominid fossils, including "Lucy" (*Australopithecus afarensis*) found in Ethiopia. Indeed, humans are all mammals, and the Cenozoic Era represents our shared history as evolving organisms during the Age of Mammals!

Primary Park Interpretive Themes and Suggested Themes

Each fossil park has developed primary interpretive themes that address the significance of that park. The selected park themes listed below relate to topics highlighted in this manual. Themes listed below were compiled from Long Range Interpretive Plans (LRIPs) or other park documents. Box 2.3 suggests additional themes, developed by the author, that focus on evolving ecosystems and may be applicable to individual parks or the Cenozoic fossil parks collectively.

Agate Fossil Beds National Monument (Theme in early draft form, LRIP in development)

“America's vast interior plains first took place during the Miocene epoch when many now extinct animals adapted to the new food source of grass. Important discoveries made at Agate Fossil Beds include such animals, some new to science, as well as traces of the actual environments they lived in.”

Badlands National Park

“The Badlands fossil and geological record reflects changing climates and the diversity, abundance and evolution of life; its study provides insight into the survival of species.”

Florissant Fossil Beds National Monument

“The Florissant Formation’s world-class fossil resources, comprising one of the most complete records of a late Eocene biotic community, provide excellent opportunities to explore changes in the Earth’s systems over time using science as a way of understanding.”

Fossil Butte National Monument

“Fossil Butte National Monument provides an opportunity to study the abundant, diverse, and exquisitely-preserved fossil specimens of Fossil Basin and the well-preserved rock record of the basin itself, enabling us to understand the surprising array of plants and animals that inhabited this system of lake environments during the early Cenozoic Era (Age of Mammals).”

“Carefully excavated and painstakingly prepared, fossils reveal evidence of ancient life. The wonder and mystery of evolution and extinction in the early Cenozoic Era drive the scientific research at Fossil Butte National Monument.”

“Climate change is evident when comparing the fossil evidence of a subtropical environment to the semi-arid sagebrush steppe ecosystem of Fossil Butte National Monument today. Studying these fossils reveals how climate and life are intrinsically linked and continually changing, helping us better understand changes through time.”

Hagerman Fossil Beds National Monument

“The monument’s fossil record includes plants and animals (including the Hagerman Horse) that lived at Hagerman about 3.5 million years ago in a wet, mostly forested floodplain.”

“The present monument looks very different from the way the area looked during the Pliocene. Vegetation is dominated by an arid sagebrush/grass complex with riparian species along the Snake River. Wildlife includes significant seasonal waterfowl populations.”

John Day Fossil Beds National Monument

“Within the John Day Fossil Beds there are great numbers of fossils, there is a great diversity of fossils, the fossils are well-preserved, they represent a long time span, and we can date them, so this is a wonderful place to study earth history.”

“The large sequence of Cenozoic fossil biotas and paleosols in the John Day region shows us that climate and life are intrinsically linked and continually changing.”

“There are multiple, well-preserved fossil assemblages in the John Day region that represent over 40 million years of the Earth’s history and may be dated with great accuracy.”

***Digging Deeper Box 2.1*. PAIRing visitors with parks**

Ranger Allyson Mathis of Grand Canyon NP developed a complementary way to visualize the meaning of the interpretive equation (Mathis, 2009). It uses the links of a chain to illustrate that interpretation aims to pair visitors with park resources (Figure 2.1). The acronym PAIR comprises **P**resentation Technique (talk, hike, informal rove, etc.); **A**udience Characteristics (age, education, personal experiences); **I**nterpretive Methods (analogies, stories, appropriate tangible/intangible links, theme); and **R**esource Information (content). **PAIR**ing reinforces the idea that, like a chain, interpretation is not likely to be successful if any of the links are weak or broken. It is also good to appreciate that a chain is both strong and flexible.

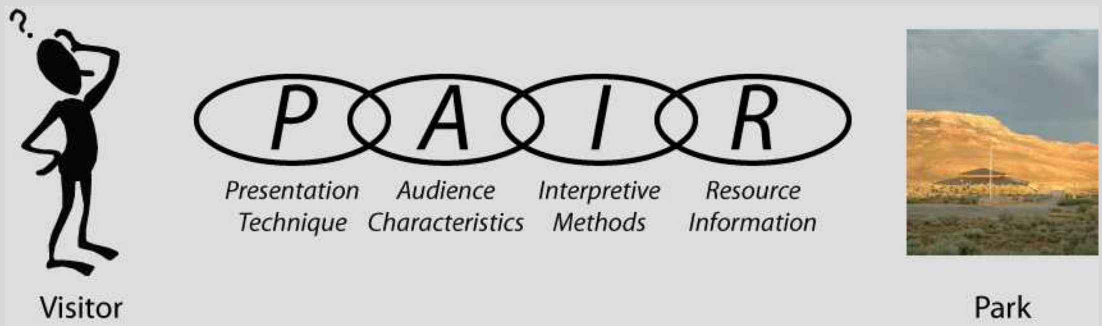


Figure 2.1. PAIRing in action! This 2003 photo of the author at Fossil Butte illustrates the PAIRing concept (NPS Photo courtesy Marcia Fagnant [Fossil Butte NM].)

Presentation Technique: 20 minute, formal interpretive talk outside the park's visitor center. Note the park's umbrellas used to shade the afternoon sun.

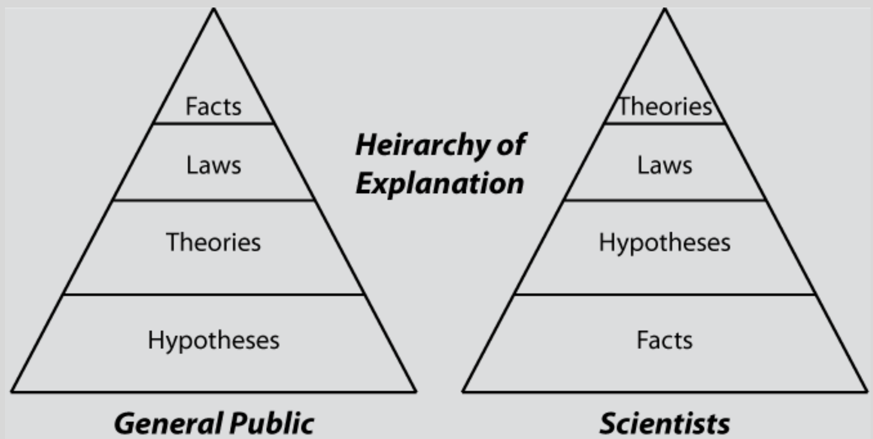
Audience Characteristics: This audience is typical for the fossil parks: mixed families, children and adults. They are generally well-educated and have some basic knowledge of the park and its fossils before entering the visitor center (Hockett and Roggenbuck, 2002).

Interpretive Methods: The program is entitled "The Road to Fossilization" and uses a road-trip analogy to describe the fossilization process. (See Chapter 3 for more on the fossilization process.)

Resource Information: Fossil Butte and Cundick Ridge dominate the landscape behind the author (outside the photo frame). This view provides a tangible link to the places where the fossils are found and where the fossilization process began 52 million years ago. Literature research and discussion with the park's paleontology staff were used to obtain scientific and other information at a level appropriate for these visitors.

***Digging Deeper Box 2.2*. Facts, Hypotheses, and Theories. Oh my!**

Understanding the scientific method and the importance scientists place on different pieces of information may help fossil park interpreters. Eugenie Scott, executive director of the National Center for Science Education (www.natcenscied.org), is a leading authority on science education, teaching evolution in public schools, and fostering a public appreciation for science. Her book *Evolution vs. Creationism* (2004) is an introduction to the subject. She includes a section on the different hierarchy the public and scientists have regarding terms such as facts, hypotheses, laws, and theories. This can lead to confusion regarding use of the terms. The following diagrams and definitions are based on information from her book. Facts are at the base of the hierarchy for scientists, not because they are unimportant, but because they form the building blocks for increasingly complex observations and ideas regarding the natural world.



Scientific terminology from Scott (2004), unless otherwise cited:

Fact: *a confirmed observation*. The building blocks of scientific knowledge. Facts can and do change following new observations, understanding, or technology.

Hypothesis: *a statement of the relationship among things*. These are usually "if…then" statements. Hypotheses guide scientific inquiry into relationships between observations (facts) and can lead to scientific explanations (theories). They are tested and can be rejected or confirmed but not "proven."

Law: *an empirical generalization: [laws] state what, under certain conditions, will happen.* Laws can change as new facts or hypotheses are developed following new observations. They can be used to predict what will happen but do not explain how it happened.

Theory: a well-substantiated explanation of some aspect of the natural world that can incorporate facts, laws, inferences, and tested hypotheses (National Academy of Sciences, 1998). Theories explain interconnected laws, facts and hypotheses and are therefore the capstone of a large body of scientific knowledge. Theories are about "how," not necessarily "why," things work. Spiritual beliefs can delve into the "why" something is observed.

Figure 2.2. Can you spot the tangibles at Carnegie Hill in Agate Fossil Beds NM? Left: Upon first glance at the ground of Carnegie Hill, one of the main historic fossil quarries, visitors may not notice the abundance of fossil bone fragments. Right: Interpreters can point to a few bones (arrows), and then visitors' eyes are opened to the incredible number of fossil fragments carpeting the quarry floor. This also provides good opportunity for resource protection and stewardship messages. By holding one of these tangible fossils, visitors are able to quite literally touch part of a 19 million-year-old rhinoceros. The very spot where they are standing right now is where that animal died and was buried. Interpreters can link these tangibles to the intangibles of geologic time and fossilization processes—or even universal concepts such as struggle for survival and death, using theme statements. (Pen for scale. Photo by Jason Kenworthy.)

Digging Deeper Box 2.3. Suggested Themes

The author developed the following interpretive themes to highlight the main messages of this manual. Additional themes are presented in subsequent chapters. They are included here as ideas to help interpreters develop themes that link the Cenozoic fossil parks. Let your individual passions drive your interpretation. That spark will catch fire!

Primary Theme for the Manual:

The colorful sedimentary layers of the Cenozoic fossil parks preserve a colorful past of ever changing landscapes, climates, and life as well as clues about change affecting our lives and futures.

Potential Sub-Themes

Chapters in the book of Earth's history remain closed until paleontologists peel back the pages illustrated by fossils and numbered by volcanic layers.

From death to discovery, the rough road to fossilization is riddled with exits and dead ends.

The active geologic landscape of the American West, including rising mountains and erupting volcanoes, developed and preserved the paleoecosystems of the Cenozoic fossil parks.

Global and regional climate change contributed to the transformation of Cenozoic fossil park ecosystems from near-tropical forests and lakes on a "greenhouse" Earth to cooler and drier woodlands, savannahs, and grasslands on an "icehouse" Earth.

The Cenozoic fossil parks preserve fossils of horses that adapted, evolved, and went extinct as climate changed and ecosystems evolved.

Just as grasses are important fuel for our lives, ancient horses evolved and took advantage of grassland's new fuel.

Chapter 3

Three interpretive opportunities to connect visitors to the Cenozoic Era, fossils, and parks.

Each interpretive opportunity is unique and driven by the visitor and the setting, yet there are common types of questions frequently posed to interpreters at the Cenozoic fossil parks: *How old is it? What is a fossil?* and *Were all these fossils found here?* Answers to these three questions can connect visitors to the Cenozoic Era of geologic time ("How old is it?"), fossils ("What is a fossil?"), and the significance of the park's sense of place and NPS resource stewardship mission ("Were all these fossils found here?"). These questions present opportunities for interpreters to not only connect visitors to the tangible resources of the park, they also form a foundation to interpret climate and ecosystem change, and to present the resource management and stewardship missions of the parks.

1. How old is it?

The question "How old is it?" provides an interpretive challenge: connecting the geologic intangible of **deep time** to the tangible rocks and fossils of the parks. Comprehension of geologic time provides the framework to discuss the chronological story of global climate change during the Cenozoic Era. This section will illustrate how paleontologists know when certain fossils lived within a park region. There are two basic approaches for determining the age of geologic materials: relative dating and absolute dating (Figure 3.1). **Relative dating** techniques provide the sequence of geologic events through time, even if the exact time for each event is unknown. **Absolute dating** techniques use a variety of laboratory measurements to determine the actual age of a rock, mineral, or fossil. **Radiometric dating**, which utilizes known decay rates of **radioactive** elements, is the most common type of absolute dating used in the Cenozoic fossil parks.

<u>Using Fossils to Tell Relative Time</u>

The fossils found within the Cenozoic fossil parks can be used to tell relative time. Relative dating techniques take advantage of the **principle of superposition**, where younger rock layers are on top of older layers. This is just like stacking pancakes as they come off the griddle: the first ones done are at the bottom of the stack, the most recent one is at the top. Another useful tool is the **principle of faunal succession.** This rule states that rocks from certain ages have distinctive groups of fossils (**assemblages**) that together form a unique, non-repeating sequence globally. In other words, specific groups of fossils are only found in rocks of certain ages. An analogy for this process would be that American cars with large tail fins were only built from the late 1950s to the early 1960s. Seeing one on the road today (a "fossil" car) provides a relatively easy method to date a car to a particular decade. Interpreters can illustrate relative dating using family groups of visitors (Box 3.1).

Beginning in the 1700s, geologists used the principles of superposition and faunal succession to assign rocks to particular geologic eras (Paleozoic, Mesozoic, Cenozoic), periods (for example: Cambrian, Jurassic, Paleogene, "Tertiary"), and epochs (for example: Eocene, Pliocene, Pleistocene) even though there was no reliable method to determine an absolute age (how many million years old) of the rocks and their fossils. This established the framework for the geologic time scale utilized today (Figure 1.2). Most divisions in the time scale corresponded to changes (extinctions) in groups of fossils. For example, the largest extinction in Earth's history occurred at the end of the Permian Period, forming the major division between the Paleozoic and Mesozoic eras. The extinction at the end of the Mesozoic Era—when dinosaurs disappeared—ushered in the Cenozoic Era (the Age of Mammals) (Box 1.3).

In western North America, assemblages of mammal fossils, including many from the Cenozoic fossil parks, were used to establish a relative time scale for the North American land mammal ages (NALMAs) (Wood and others, 1941; Woodburne, 2004b). This is analagous to the dynasties of China, whereby different royal families reigned during different time periods. Historians can refer to the Ming Dynasty for example, which was in place from 1368-1644. Different dynasties ruled during different time periods and for different durations. Likewise different fossil mammal "dynasties" are found throughout the American West. As shown in Figures 3.2 and 3.3, the fossil assemblages found in each park can be assigned to a particular NALMA, which is then tied to a particular epoch. See Box 3.2 for suggestions on interpreting the names of the Cenozoic epochs. The NALMAs were named for geographic areas where those fossils are common. Using fossils to tell time is a process called **biochronology**. Even without knowing the absolute ages of the different assemblages, the rock layers containing the fossils can be arranged in chronological order to tell a story. In regions of the world that do not have many dateable ash layers, or in very thick sequences of sedimentary rocks, biochronology of the observed fossils may be the only method of determining the age of a rock sequence.

Using Volcanoes to Determine Absolute Time

As in Box 3.1 "Relative Dating with Relatives" example, it is impossible to know exactly when the various family members were born unless you ask them or have access to their birth certificates or driver's licenses. Only since the mid-1900s have geologists had the proper tools to "ask" rocks and fossils how old they are via radiometric dating, the most common type of absolute dating. Because sedimentary rocks lack the appropriate minerals for radiometric age dating, fossils are the only practical means of dating most sedimentary rocks. Volcanoes have been erupting in the American West for more than 100 million years and continue to erupt in recent time in the Cascade Range, Basin and Range Province, Rio Grande Rift, and Yellowstone. Not only did the erupting volcanoes provide some of the materials for rapid burial and fossilization, the dozens of ash layers found within the Cenozoic fossil parks also provide the radioactive minerals necessary for absolute dating. Fossils found above a volcanic ash layer are younger, and those below are older, according to the principle of superposition. Volcanic ash layers thus provide an age range for fossils found in sedimentary rocks between successive ash layers (Figures 3.2, 3.3, and 3.5). Chapter 4 highlights the roles of volcanoes in the preservation and interpretation of paleoecosystems.

To understand radiometric dating it helps to understand the relationships between atoms, elements, minerals, and rocks as shown in Box 3.3. Radioactive isotopes (parents) of elements are unstable and decay to stable isotopes (daughters). The time it takes for half of a sample of radioactive parent to decay to the daughter form is called the **half life** (Figure 3.4). After one half life, half (50%) of the parent has decayed. After another half life passes, half of that decays, leaving 25% of the parent; 75% of the sample is daughter. By measuring the ratio of the radioactive parent to the stable daughter, geologists determine how many half lives have passed since the mineral formed. Multiplying the number of half lives passed by the length of the parent isotope's half life yields the age of the sample.

Volcanic ash layers contain minerals such as sanidine and biotite that are rich in the element potassium (K). The decay of unstable potassium-40 to stable argon-40 (Figure 3.4) forms the basis for a radiometric dating technique commonly used to date ash layers found in the Cenozoic fossil parks. The element argon (Ar) is a gas. Any argon that was in the molten material escaped when the volcano erupted. Once the molten material cools as volcanic ash, **crystals** of biotite and sanidine form, which originally have potassium but no argon. Over time, the radioactive isotopes of potassium-40 in the mineral crystals decay to stable argon-40. But the argon-40 is trapped in the solid crystal lattice of the biotite or sanidine, so it has nowhere to go and builds up in the mineral crystal. As long as the crystal is not damaged, and shows no sign of weathering, geologists measure the ratio of potassium-40 to argon-40 to determine how many half lives have passed since the ash was deposited. Powerful microscopes are used to select mineral crystals that show no sign of damage just like tamper-evident seals at the grocery store show that the container has not been previously opened. The potassium-argon dating technique has been refined into the more precise argon-argon technique now used in many of the Cenozoic fossil parks, but the underlying principle is the same (Boxes 3.4, 3.5).

<u>Deep Time and the Cenozoic Fossil Parks</u>

Where do the Cenozoic fossil parks fit into the 4,540 million year history of Earth? Figure 1.2 shows the geologic time scale with the last 65.5 million years (Cenozoic Era) highlighted. The Paleogene and Neogene (together commonly referred to as the "Tertiary") periods make up only 1.4% of Earth history. Despite being quite recent, as far as humans are concerned, this time period generally receives less popular attention than other time divisions (for example, the Mesozoic Era with dinosaur fossils). The popular movies *Jurassic Park* (older than the Cenozoic fossil parks) and *Ice Age* (younger than the Cenozoic fossil parks) provide context for the time of the Cenozoic fossil parks, as those movies are about more "familiar" fossils (Box 3.6).

The concept of deep geologic time spanning thousands of millions of years is nearly impossible for humans, with a life span of tens of years, to grasp (Box 3.7). There are many interpretive analogies that have been developed to compress the inaccessible immensity of geologic time into something people may grasp based on their own personal experiences. Some are time-based like that of Prothero (2006), who compressed 4,540 million years into one calendar year (recorded history begins about one minute before midnight on December 31). Others are spatial, using distance to represent time, such as Lillie (2005) who utilized a football field (human history is the size of a dimple on the football) or Wagner's (2002) outstretched arms (human history could be removed by filing your nails). Both John Day Fossil Beds NM (Clarno Unit) and Florissant Fossil Beds NM have geologic time hikes along portions of park trails using hiking distances to represent passage of geologic time. A new, spectacular example is the "Trail of Time" recently completed at Grand Canyon NP (Karlstrom and others, 2008).

Continuing the road trip analogy from earlier in this chapter, geologic time can be compressed into the distance of a cross-country road trip from Washington, D.C. to Berkeley, California (Figure 3.6). The start (formation of the Earth) and end (present-day) points are actually the Smithsonian National Museum of Natural History in D.C. and the University of California Museum of Paleontology in Berkeley[3]. The road trip covers 2,806 miles, primarily on Interstate 80 so that every mile of highway travelled covers 1.6 million years of geologic time. For international visitors, the 4,516 km over 4,540 million years works out to about 1 million years per kilometer. Nearly all visitors to the fossil parks in particular, share the tangible experience of having just travelled many miles in a car. At the spatial scale of 1 mile equals 1.6 million years, the concept of deep time becomes slightly more understandable. At this scale, you could fit 25 years to an inch (my nearly 32-year life would be represented by the length from the tip to the first knuckle of my thumb) and the nearly 234-year history of the United States would be covered in a mere 9.1 inches, the size of print from the upper to the lower margin of this page. The 6,000 years of recorded human history would be passed by in a mere 19.6 feet (a bit longer than a Chevy Suburban). At this scale, you would have to drive all the way from Washington, D.C. to more than halfway through Nevada before getting out of the Precambrian part of geologic time. The Mesozoic Era, the Age of Dinosaurs, starts just over the California line and lasts for about 115 miles. The Cenozoic Era, the Age of Mammals, only covers the last 40.5 miles of the trip and the Paleogene and Neogene periods covers the first 39.4 miles of that. At highway speeds, you could drive through the entire Paleogene and Neogene periods in a little over half an hour! The most recent "ice ages" occurred

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[3]These two institutions, incidentally, maintain very large fossil collections from the Cenozoic fossil parks. Readers may recognize the trip generally follows the route of author John McPhee, as compiled in his book *Annals of the Former World* (Farrar, Strauss, and Giroux, 1998).

during the Pleistocene Epoch with the most recent ice retreat marking the beginning of the Holocene Epoch. The last 20,000 years of modern human evolution thus occurred in just the last 66 feet of the road trip (shorter than the length of an 18-wheeler). Table 3.1 shows the “mileages” for the different time units of the geologic time scale.

2. What is a fossil?

One of the more common questions posed at the Cenozoic fossil parks is “What is a fossil?” While a simple identification of the fossil may satisfy the basic curiosity of a visitor, the question can also be used as an opportunity for sharing the geologic definition of fossil, and the geologic story behind the formation of a fossil. At its most basic, the term “fossil” is from the Latin *fossilus* meaning “dug up.” The National Park Service defines a **fossil** as “Any organic remains (plant or animal), trace, or imprint that has been preserved by natural processes within a geologic context.” (National Park Service, 2001) or more simply “evidence of life preserved in a geological context” (Santucci, 2002). Although visitors may have misconceptions about the term “fossil,” those misconceptions can provide opportunities for additional information and interpretation (Box 3.8).

A fossil can provide both tangible information and intangible ideas. The actual remains may be either a **body fossil** or a **trace fossil**. Body fossils are any “parts” of the actual living thing: bones, teeth, insect bodies, shells, feathers, leaves, fruits, flowers, nuts, etc. Trace fossils are “prints, parking, and poop”—evidence of a living thing’s interaction with its environment, without any part of the actual organism. Footprints, trackways, swim traces, burrows or dens, dung beetle balls, rhizoliths (root traces), and even **coprolites** (fossil feces) are a few examples of trace fossils from the Cenozoic fossil parks. Body fossils commonly receive more attention because they are pieces of living things, but every body fossil records the death of an organism. Trace fossils are valuable because they can record a moment of an organism’s life when it was still alive!

The **geologic context** of a fossil provides not only tangible evidence of geologic processes but also intangible meaning behind the tangible fossil remains. Identification and classification (**taxonomy**) of fossils in the Cenozoic fossil parks allow paleontologists, interpreters, and visitors to know what ancient plants and animals lived in the parks. But without studying the geologic context (type of rock; specific layer; other plant and animal fossils), there is no story to go along with the remains. Not studying the context of a fossil would be like going to a Broadway musical, reading the cast of characters and leaving before the show started. You would have an idea about who was there and some of their background and history, but would have no idea how those characters interacted with each other, and how their relationships developed during the course of the performance.

In the 20th century, the science of paleontology evolved toward better documentation of a fossil's context. Many early fossil hunters collected fossils with locality descriptions that today would be much too vague. Now paleontologists record where the fossil was found via GPS, what layer it was in, as well as a host of other information. Once a fossil is removed from the ground it cannot be put back, so paleontologists strive to record as much information as possible regarding the context of each fossil. Without such detailed context information, our knowledge of paleoecosystems (Chapters 4, 5, and 6) would be greatly reduced and precise correlations between parks would be impossible.

The Rough Road to Fossilization

The formation of fossils from once-living organisms can be a powerful interpretive tool. For most visitors, fossils are just remains "turned to stone." But fossils are formed in a variety of ways and in many different contexts. The "Road to Fossilization" is not an easy one (Figure 3.7). From death to discovery, the road is riddled with exits and dead ends!

As soon as an organism dies, it starts along the road to fossilization (Figure 3.8). For some humans, death is considered the "end," but for the fossilization processes, it is just the beginning. Rapid burial of the remains is key to minimizing destruction and dispersal due to decomposers, scavengers, **physical weathering**, and erosion. The science of **taphonomy** investigates what happens to an organism's remains after death. The Cenozoic fossil parks are excellent places to study ancient taphonomy because of the diversity and abundance of fossils. Within the Cenozoic fossil parks, there are four primary **depositional environments** in which remains were buried: floodplain in a river basin (**fluvial**); lake bottom (**lacustrine**); in volcanic mudflows (**lahars**); and wind-blown (**eolian**) settings (Chapter 4). Agate Fossil Beds NM, Badlands NP, Hagerman Fossil Beds NM, and John Day Fossil Beds NM (Turtle Cove, Kimberly, "Haystack Valley", Mascall, and Rattlesnake strata) preserve fossils from fluvial environments. Fossil Butte, Florissant Fossil Beds, and John Day Fossil Beds (Bridge Creek strata) preserve fossils from lacustrine environments. The redwood stumps at Florissant Fossil Beds NM and some of the plant fossils from the Clarno Formation at John Day Fossil Beds NM are preserved in lahars. The Harrison Formation at Agate Fossil Beds NM and part of the Brule Formation of Badlands NP contain extensive eolian deposits.

Once remains are buried, they may undergo one or more types of fossilization, including **unaltered remains**, **permineralization**, **replacement**, **recrystallization**, **compression/carbonization**, and **molds/casts/impressions** (Figures 3.9 to 3.14). Fossilization does not follow a set recipe. It is highly dependent on local conditions including depth of burial, type of sediment, amount of groundwater, and minerals dissolved in the groundwater (Boxes 3.9 and 3.10).

After a fossil forms, it is not yet at the end of the road (Figure 3.8). Plate tectonic processes can increase temperature and pressure, so that rock layers are deformed, metamorphosed, and even melted. Any fossils in these rocks would be severely deformed or destroyed. Because the Cenozoic fossil parks today are in tectonically quiet areas, the fossils face a much greater threat—erosion. While the fossil parks were areas of deposition and burial during the Cenozoic, today they are in regions that are exposed to the elements and eroding, as illustrated by their dramatically carved landscapes (Figure 3.15). Most fossils exposed at the surface are eventually destroyed by wind, water, and gravity.

Discovery: The end of the road to fossilization

The very, very few organisms that were not eaten, decomposed, or eroded; managed to be buried rapidly and underwent fossilization; and then escaped the ravages of time and erosion, still need to be discovered and recognized as fossils before they can be studied by paleontologists or appreciated by visitors. There are two primary methods of discovering fossils: **quarrying** and **prospecting**. The main difference is that during quarrying, paleontologists keep digging in one spot looking for fossils; during prospecting, paleontologists do not dig until they find a fossil.

Just like mines or stone quarries, where excavations take place in a defined area, fossil quarries are excavations into known fossiliferous layers. Paleontologists remove rock layer by layer to expose fossils buried within. This process speeds up natural erosion by mechanically removing rock and fossils in a controlled manner. The lake bed deposits of Fossil Butte NM, Florissant Fossil Beds NM, and John Day Fossil Beds NM (Bridge Creek) are commonly quarried (Figure 3.16). Quarry excavations also uncovered fossils at the Big Pig Dig in Badlands NP (2008 was the 15th and final summer of excavation!), the Fossil Hills of Agate Fossil Beds NM, the Hagerman Horse Quarry in Hagerman Fossil Beds NM, and the Hancock Mammal Quarry in John Day Fossil Beds NM. Such excavations are only successful in areas where fossil remains are concentrated, like the watering holes of Agate Fossil Beds NM and Badlands NP's Big Pig Dig, or widespread throughout a particular layer or layers, like the lake deposits of Fossil Butte NM.

For the majority of fossiliferous layers within the parks, prospecting is the primary method of fossil discovery because the fossils are scattered randomly throughout a layer or within a geographic area (a location where fossils have been discovered is called a fossil **locality**). Paleontologists at the Cenozoic fossil parks spend a lot of time with their eyes on the rocks in gullies and other erosional areas looking for naturally exposed fossils (Figure 3.16). Fossils discovered in this manner may be excavated if they are rare, particularly well preserved, or of scientific value.

Regardless of how it was discovered, the fossil continues on a new road—it may be collected or left in place, identified, described, or put on display. It can then help visitors connect with the past and its changing climates and evolving ecosystems (Chapters 4, 5, and 6).

<u>One in a billion</u>

So just how rough is the road to fossilization? Estimates vary, but perhaps only one bone in one *billion* becomes fossilized. As related by Bryson (2003), if this holds true, then the complete fossil legacy of all Americans alive (approximately 300 million) with 206 bones each would only be about 62 bones (about 30% of *one* skeleton; Figure 3.17). Another way of grasping the amazing incompleteness of the fossil record comes from Prothero (2004). There are more than 4.5 million plant and animal species alive on Earth today. But the entire known and described fossil record, covering 3 billion years of Earth history from bacterial fossils to "ice age" mammoths is less than one million species. Clearly humans are only aware of a very small fraction of life that has existed on Earth. Many fossils that survived a long and treacherous road to fossilization have simply eroded away or are still buried, awaiting discovery (Figure 3.18).

Most species did not even have a chance to travel too far down the road, based on the environments where they lived. For example, mountain tops and very humid areas would not preserve many fossils due to high rates of erosion or decomposition. The Cenozoic fossil parks today are records of past life where deposition of sediment and burial were taking place. Today, as demonstrated by the parks' predominant "badlands" landscapes, erosion far outpaces deposition—they will not likely preserve great records of what is living there now! The Cenozoic fossil parks are spectacular examples of beating the odds: large numbers of well-preserved fossils. But even their fossil diversity pales in comparison to the actual biodiversity that must have existed during the Cenozoic time periods they represent.

3. Were all these fossils found here?

Visitor centers at the Cenozoic fossil parks serve as museums for each park's fossils. Unlike large natural history museums that feature a wide variety of fossils and natural history items from across the country or around the world, exhibits at each visitor center feature fossils found within the park, or in the local area. This is a unique experience for visitors and they frequently comment "Were all these fossils found here?!" Stepping outside presents visitors an opportunity to see the rock layers where the fossils in the visitor center were discovered. The parks thus provide a unique tangible experience of being able to experience fossils ***in situ*** and provide an intangible link to a visitor's sense of place. For example, at Florissant Fossil Beds NM, visitors are able to stand next to 15-foot-tall (4.6 m) fossil redwood tree stumps. Those trees (Figure 3.12) have been rooted in that exact spot for 34 million years! Such experiences provide an unmatched sense of place because visitors can share the same place as the now-fossil animal or plant.

The NPS fossil parks are unique in this aspect (Hatcher, 2006). Fossils from the parks are on exhibit in museums around the world and millions of people can experience them. But only visitors to the actual parks experience the tremendous sense of place and connection to where the fossils were originally found and are still being found. Connecting to a visitor's sense of place is interpretively powerful. One of the tenets of NPS interpretation is that facilitating connections between a visitor and the park will allow visitors to care *about* the resource so that they may care *for* the resource (Larsen, 2003). This might then lead to a self-realized answer to another common question: "Where can I dig for fossils?" (Box 3.11)

The sense of place can be a starting point for long-term climate change interpretation (Chapter 5). Visitors to Fossil Butte NM can view palm fronds, crocodiles and *Phareodus* fish whose modern relatives are found in subtropical southeast Asia. But the fossils are described from ancient lake beds in what is now the high desert of Wyoming. This is a startling difference made more real by the modern-day, dry sagebrush landscape of the park. The changes apparent between the fossil ecosystems and modern ecosystems of each park are illustrated by fossils from all the parks (see park landscape photos and murals or reconstructions in Chapter 1). This creates opportunities to connect with visitors from other regions or visitors' travel experiences. For example, visitors from the southeastern United States come from a climate similar to that recorded by the 33-million-year-old Bridge Creek assemblage of John Day Fossil Beds NM. Visitors who have traveled to Africa would have recognized the 19 million-year-old savannah watering hole where the mixed-grass prairie of Agate Fossil Beds NM is today. Surrounded by evidence of past climate changes also presents opportunities to interpret modern climate change (Chapter 7).

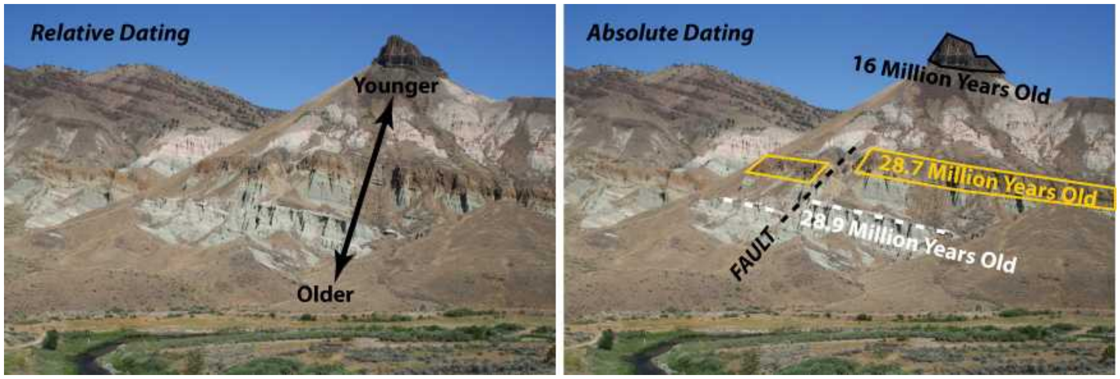


Figure 3.1. Dating rock layers from Sheep Rock at John Day Fossil Beds NM in a relative sense (left) and an absolute sense (right). In relative dating, rocks and fossils from lower layers are older than those from upper layers. In absolute dating, an age can be assigned to some of the volcanic layers and provide an age range for fossils found above or below them, like page numbers in a book. One of the features that make the Cenozoic fossil parks so valuable scientifically is the abundance of volcanic ash layers that provide the radioactive minerals used in absolute dating. Note that the layers on Sheep Rock have been cut by a fault. When did the faulting occur? Before or after the deposition of the ash layers? How could this be determined? (Photo by Robert J. Lillie.)

***Digging Deeper Box 3.1*. Relative Dating with Relatives**

One way to help visitors appreciate the differences between relative and absolute dating is to ask a family group to line up in order from oldest to youngest. Then, a basic family history can be established. For example, Grandma was born before her son who is older than his son. Interpreters thus have them organized in a relative sense, that is generations going from oldest to youngest. Similarly, the geologic time scale was created to reflect the sequence of formation of rock layers, dividing them into different “generations” (geologic Eons, Eras, Periods, and Epochs). Even though you can establish a basic family history without knowing anyone’s actual age, adding in their ages helps complete the story. Likewise absolute dating techniques provide the chronological framework for the geologic history laid out in the fossils of the Cenozoic Fossil Parks. In this sense, volcanic ash layers would be like the grandma’s, son’s, and grandson’s birth certificates, that establish the exact year, month, and date each were born.

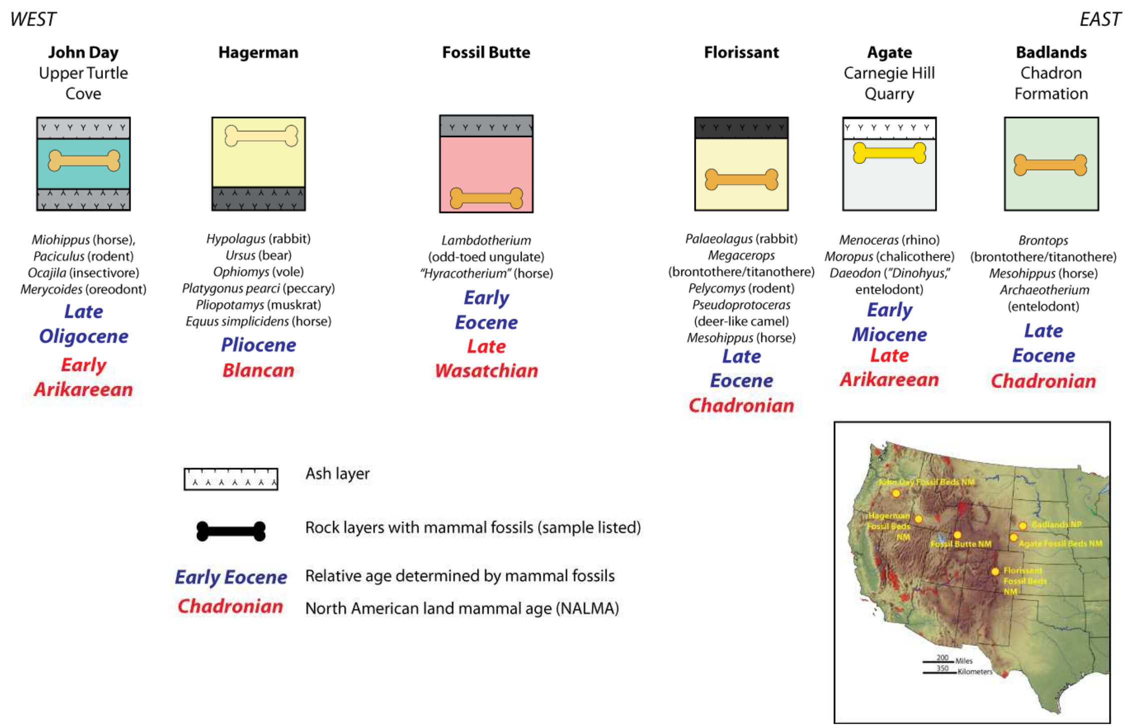


Figure 3.2. Fossils tell relative time. The boxes in the illustration represent fossil-bearing rock layers in each park. They are arranged from west to east (left to right). How can they be arranged chronologically (that is, from oldest to youngest)? The mammal fossils found in the layers can be used to determine a relative age for the rock layers, shown above in blue text. They can then be placed in chronological order to tell a story without referring to exactly when the story took place (Figure 3.3). Figures 3.4 and 3.5 show how the volcanic ash layers can be used to create an absolute chronology. Mammal age determinations follow chapters in Woodburne (2004b) and identifications in Albright and others (2008), Gunnell and others (2002) and McDonald and others (1996).

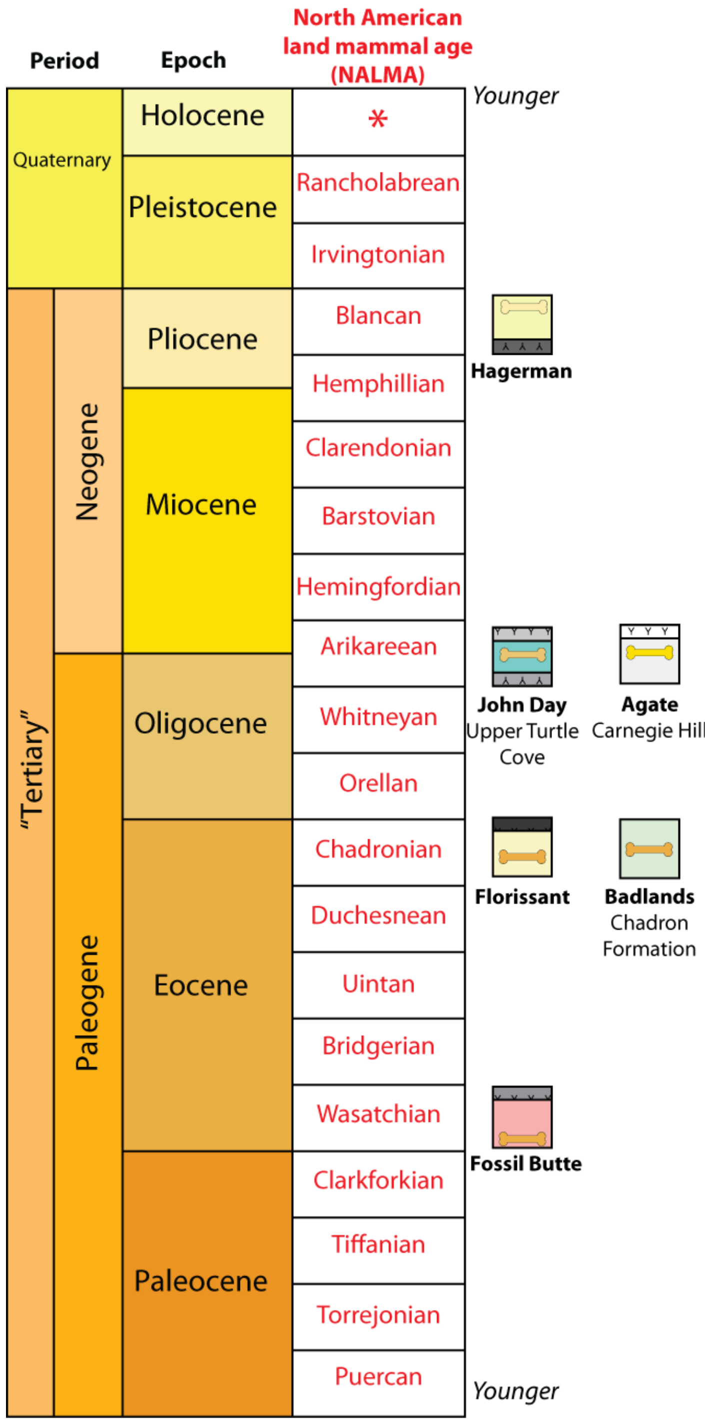


Figure 3.3. The relative ages and North American land mammal ages (NALMAs) from Figure 3.2 place mammal fossils of the Cenozoic fossil parks into chronological order, tied to the geologic time scale. Even without numerical ages, there is some sense of how much older mammals from Fossil Butte NM are compared to those of Hagerman Fossil Beds NM. * = there is no NALMA for the Holocene.

Digging Deeper Box 3.2*. *Say What? Epoch Etymology

Modern dating techniques allow interpreters to interpret the actual age of a fossil. For example, an interpreter could make a statement like: “The titanotheres of Badlands lived 37 million years ago” rather than just using a time interval: “Titanotheres lived during the Eocene.” The names of geologic units have a story to tell, if one can speak the language! Here’s a cheat sheet for the Cenozoic Era.

Many publications use the term Tertiary Period, referring to the Paleocene through Pliocene epochs. Paleozoic rocks used to be called “Primary” and Mesozoic rocks were referred to as “Secondary,” providing some context for the Tertiary (“third”) and Quaternary (“fourth”) periods.

The names “Paleogene Period” (for the Paleocene, Eocene, and Oligocene epochs) and “Neogene Period” (for the Miocene and Pliocene epochs) are used increasingly instead of “Tertiary.” The suffix “gene” is from the Latin *genus* meaning “kind, race, or stock” while *paleos* means “ancient” and *neo* means “new,” making the Paleogene “ancient kind” and the Neogene “new kind.”

As shown in Figure 1.2, the Cenozoic (“recent life”) Era is divided into 7 epochs, 4 of which are part of the Paleogene and Neogene periods spanned by the Cenozoic fossil parks. The epochs were established by paleontologists and geologists as a relative time scale, and their names reflect this.

The word root -*cene* (from the Greek *kainos* meaning “recent”) is common to all, and is the same root found in “Cenozoic.” Paleontologists studying fossils from the Cenozoic Era compared the diversity of fossil species from the different epochs to those of today. The epochs were named on the basis of how many recent animals were found in the fossil ecosystems.

The epochs are arranged youngest to oldest, top to bottom:

Holocene: *holos* “entire;” Holocene = entirely recent

Pleistocene: *pleistos* “most;” Pleistocene = mostly recent

Pliocene: *plio* “more;” Pliocene = more recent

Miocene: *mio* “less;” Miocene = less recent

Oligocene: *oligos* “few;” Oligocene = few recent

Eocene: *eos* “early, dawn;” Eocene = early recent, or dawn of the recent

Paleocene: *paleos* “ancient;” Paleocene = ancient recent

Etymology (“word origin”) from Brown (1956).

<u>Digging Deeper Box 3.3</u>. Atoms, elements, minerals, and rocks are time capsules

Protons, neutrons, and electrons are the building blocks of **atoms**, which are in turn the building blocks of **elements** such as carbon (C), silicon (Si), potassium (K), oxygen (O), iron (Fe), aluminum (Al) and magnesium (Mg). Elements combine in specific quantities and structures to make solid compounds known as minerals (for example quartz, which has the chemical formula SiO_2). Combinations of minerals make rocks.

In order to radiometrically date rocks, geologists select rocks that have minerals containing radioactive (unstable) elements. Such elements lose parts of their atomic nuclei over time so that they change (decay) from their unstable, radioactive isotope to a stable, non-radioactive isotope.

For example, when a volcano erupts, molten material is ejected and blankets a large area. As the volcanic ash cools, it forms solid material made up of minerals. Some of the elements in the volcanic ash minerals are radioactive and start to decay as soon as the mineral cools. The radiometric "clock" is thus set to time zero when the ash fell.

<u>Digging Deeper Box 3.4</u>. Argon-Argon Dating

One drawback to potassium-argon dating is that the solid potassium and gaseous argon have to be measured on separate machines, introducing the potential for errors and making the resulting date less precise. A newer technique, argon-argon (argon-39 / argon-40) dating uses the same decay scheme as potassium-argon, but with a more precise twist. The sample is placed in a nuclear reactor, where it is bombarded by neutrons. The neutrons convert the radioactive potassium-40 to argon-39, which is not present in nature. The argon-39 thus becomes a substitute for the potassium-40. Measuring the ratio of argon-39 to argon-40 allows a determination of the age of the sample. Because two isotopes of the same element are being measured, they can be measured on the same machine, reducing error. In fact, with argon-argon dating techniques, volcanic ash layers tens of *millions* of years old can be dated with a precision of a few tens of *thousands* of years instead of the few millions of years possible with potassium-argon dating. For more information regarding argon-argon dating, see EarthRef (2009).

<u>Digging Deeper Box 3.5</u>. Give or take a hundred thousand years: Precision of dating techniques

From many analyses, Smith and others (2008) report an argon-argon age of 51.66 ± 0.09 million years (51,660,000 ± 90,000 years) for the K-Spar Tuff ash layer in Fossil Butte NM. The ± symbol is the scientific notation for "give or take." Just how precise is that? Even though the 90,000 year error would entirely envelop all 6,000 years of recorded human history many times over, that date is incredibly precise geologically-speaking.

In fact, 90,000 years is an error of only 0.17% on an age of 51.66 million years. That is an error of slightly more than six *days* over a period of ten *years*! Such very good precision allows for the correlation of ash beds from park-to-park and provides an excellent record of when geological events occurred in the Cenozoic fossil parks.

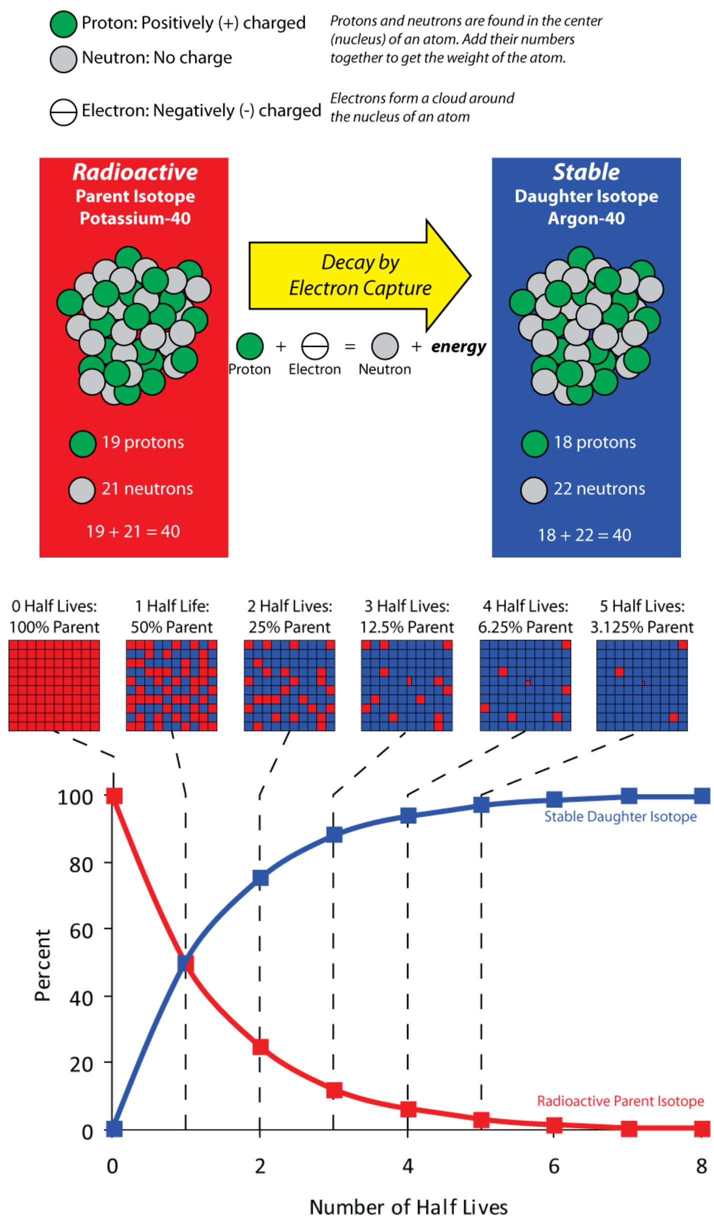


Figure 3.4. Radioactive decay is used as a rock clock. The potassium-argon rock clock uses the decay of the radioactive isotope potassium-40 to the stable isotope argon-40 (top illustration) with a half life of 1,270,000,000 years (1.27 billion years). After each half life, half of the original parent has decayed to the daughter form (lower graph). By measuring the ratio of parent to daughter isotopes in a rock, geologists determine how many half lives have passed, and thus the age of the sample. Note how little parent isotope remains after 5 half-lives. It is difficult to measure the ratios with so little parent remaining, so radiometric dating is only reliable through about 5 half-lives. Carbon-14, another isotope used for radiometric dating has a short half life of only 5,730 years. The carbon-14 method is thus not useful for samples older than about 40,000 years, which is why it is not used to date rocks from the Cenozoic fossil parks.

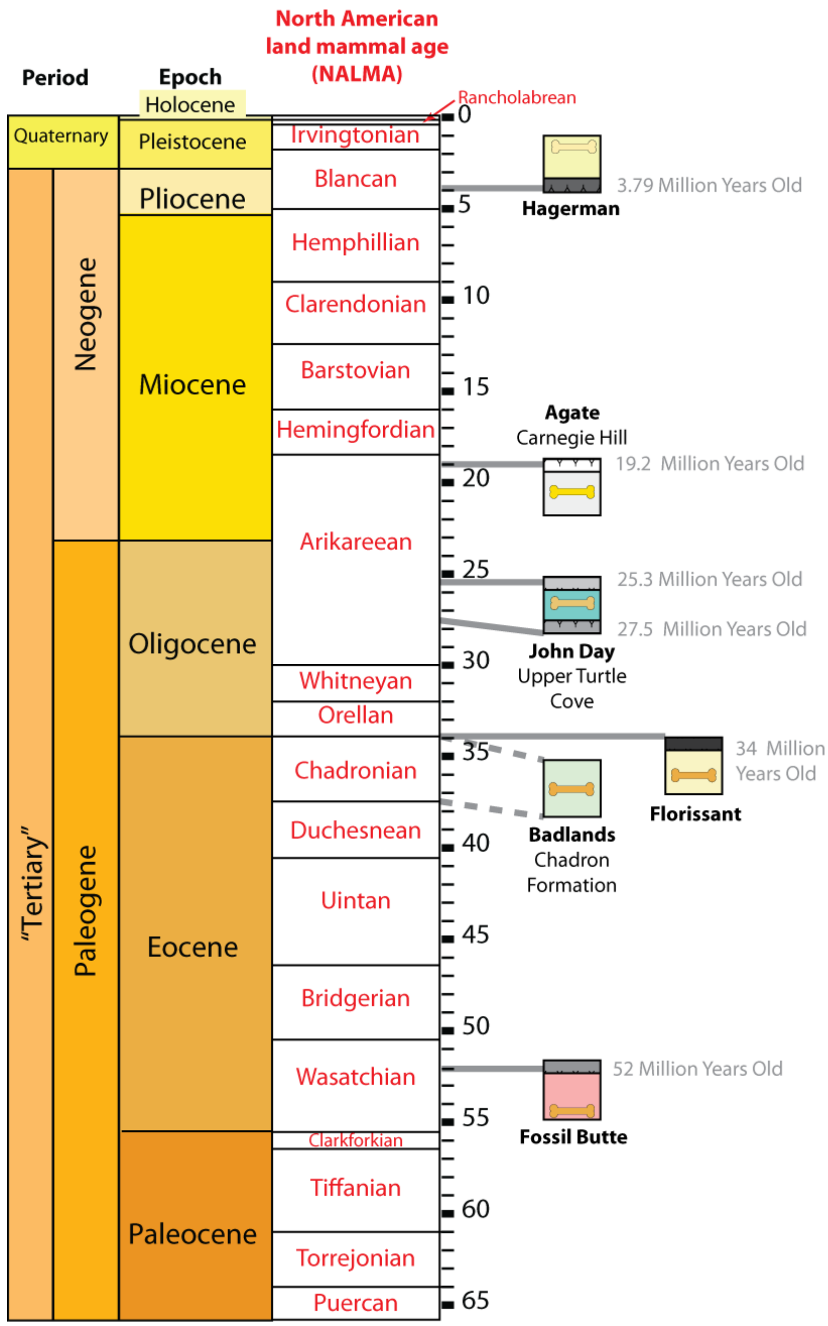


Figure 3.5. Absolute dating methods provide rock clocks for the ash layers found within fossil-bearing strata in the Cenozoic fossil parks. The principle of superposition means that the ages of the ash layers provide the minimum and maximum possible ages for any fossils found between the two ash layers. Note that the Chadron Formation mammals of Badlands are not associated with an ash layer, so the mammals are used to assign a late Eocene ("Chadronian") age, which has been determined using ash from other locations and the same fossil assemblage to be 37-34 million years old. (Volcanic ash ages are from Hunt and others [1983], Izett and Obradovich [2001], Albright and others [2008], Lloyd and others [2008], and Smith and others [2008].)

<u>Digging Deeper Box 3.6</u>. The Cenozoic fossil parks connect two movies: "Jurassic Park" and "Ice Age"

Orienting Cenozoic fossil park visitors to where they are in the geologic time scale can be a challenge because the Cenozoic Era and its epochs (see Box 3.2) are relatively unfamiliar terms. One approach is to use the popular movie series "Jurassic Park" and "Ice Age" which star some familiar fossil animals. Interpreters can ask visitors what animals were in "Jurassic Park" (dinosaurs) and what sort of ecosystems did they live in (very generally tropical, hot, warm, lush). Asking the same question for "Ice Age" usually yields wooly mammoths or saber toothed cats that tend to be associated with much colder climates. It's important to remember the stars of the two movies never co-existed as in "Ice Age 3: Dawn of the Dinosaurs"!

Once the interpreter has established the two "end members," the Cenozoic fossil parks become a bridge between the two, with the story of how mammals diversified and evolved after the dinosaurs went extinct. Another interpretive opportunity can be made showing that the world was much warmer and wetter during the age of the dinosaurs and much colder and drier during the ice ages. The Cenozoic fossil parks also bridge the climatic gap and their fossils tell the story of a world transitioning from a global greenhouse ruled by dinosaurs to a global icehouse populated by mammals (leading to human evolution).

The time interval interpreted by an individual park can be put into context as being more similar to the greenhouse world of long-ago dinosaurs or more similar to the icehouse world of recent mammals (Chapter 5). Adding absolute ages to this interpretation further reinforces the chronological connections and passage of time.

<u>Digging Deeper Box 3.7</u>. How many is a million?

Humans have a hard time comprehending numbers much bigger than 100. The idea of deep geologic time and millions of years is hard for anyone to grasp. Analogies that create a visual representation of a million common objects can help. For example:

If you count every letter in every word in this document, you would get only about 420,000 characters! Although it may seem like much more, that is still less than half of one million!

One million seconds is about 11½ days.

If you take one million adult strides—figure about 4½ feet (between 1¼ and 1½ meters)—you will have walked slightly more than 850 miles (1,360 kilometers). This is about the distance of highway travel from the visitor center at John Day Fossil Beds NM in Oregon to the visitor center at Florissant Fossil Beds NM in Colorado.

A road trip of one million miles is more than 4 times the distance between Earth and the Moon.

You have only about 100,000 to 140,000 hairs on your head.

A standard step in a staircase is about 8.25 inches (21 centimeters) high. One million steps would get you up to 687,500 feet (209,550 meters) in elevation, or about 130 miles (209 kilometers)! Hope you brought your spacesuit because you could wave at astronauts from that height. The space shuttle orbits from about 115 to 400 miles (185 to 645 kilometers) above Earth's surface.

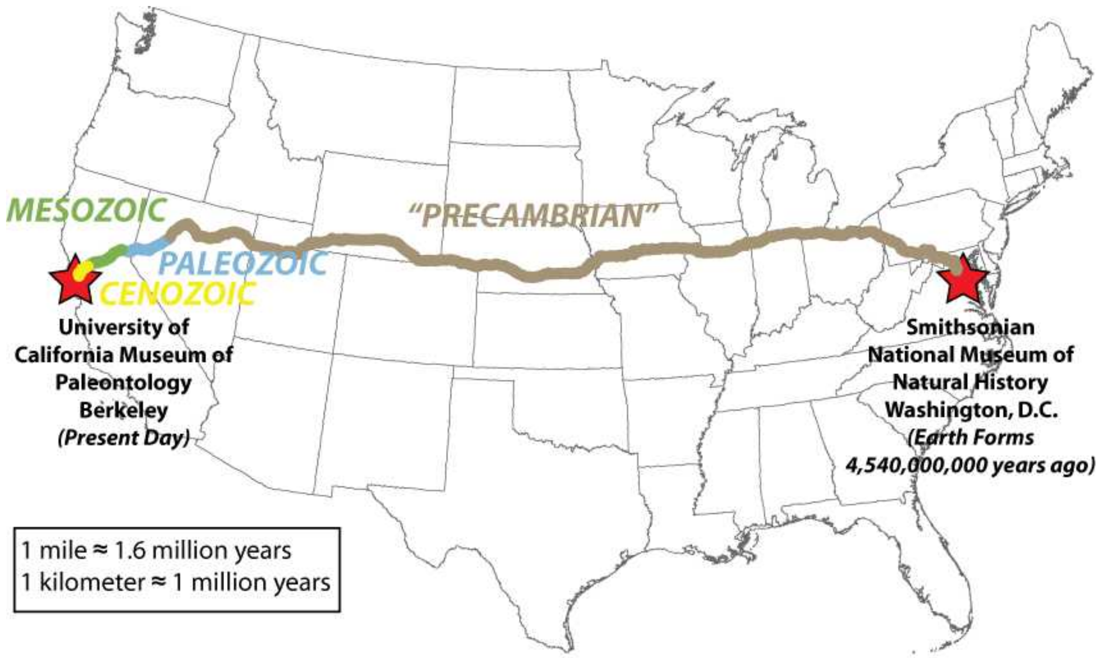


Figure 3.6. A geologic time road trip! Compressing the 4,540 million (4.54 billion) years of Earth history into a 2,806-mile long interstate road trip (mostly on I-80) means that every mile of highway spans about 1.6 *million* years of geologic time. This is a poignant comparison for visitors on vacation who have just spent many hours travelling in a vehicle. It can also be a happy-family way to respond to that question all parents never tire of hearing: "How much longer till we get there?"

Table 3.1. Using the scale of 1 mile = 1.6 million years, the geologic time scale can be converted into distances (Figure 3.6), providing one method for interpreting deep geologic time.

	Time Interval	Time Interval Begins (years ago)	Distance from Smithsonian (miles)	Nearby Town or Place	Length of Time Interval (miles)
Age of Mammals	Holocene	11,700	2,805.99	Berkeley, CA (end)	38 feet
	Pleistocene	2,588,000	2,804.40	Berkeley Marina, CA	1.59
	Pliocene	5,332,000	2,802.70	Albany, CA	1.70
	Miocene	23,030,000	2,791.77	Rodeo, CA	10.94
	Oligocene	33,900,000	2,785.05	Vallejo, CA	6.72
	Eocene	55,800,000	2,771.51	Fairfield, CA	13.54
	Paleocene	65,500,000	2,765.52	Vacaville, CA	6.00
Age of Dinosaurs	Cretaceous	145,500,000	2,716.07	Citrus Heights, CA	49.44
	Jurassic	199,600,000	2,682.63	Colfax, CA	33.44
	Triassic	251,000,000	2,650.87	Tahoe Nat'l Forest, CA	31.77
Age of Marine Invertebrates	Permian	299,000,000	2,621.20	Boca Reservoir, CA	29.67
	Pennsylvanian	318,100,000	2,609.39	Verdi, NV	11.80
	Mississippian	359,200,000	2,583.99	Patrick, NV	25.40
	Devonian	416,000,000	2,548.89	Eagle Rock, NV	35.11
	Silurian	443,700,000	2,531.77	Trinity, NV	17.12
	Ordovician	488,300,000	2,504.20	Lovelock, NV	27.57
	Cambrian	542,000,000	2,471.01	Humboldt, NV	33.19
	"Precambrian"	4,540,000,000	0	Washington, DC (begin)	2,471.01

***Digging Deeper Box 3.8*. Fossil Follies and Misconceptions**

Visitors (and interpreters!) may have a number of common misconceptions regarding fossils. One is that all fossils are organisms "turned to stone." But there are many different ways a fossil can form. Another common misconception is that a fossil must reach a certain "magic age" to be considered a fossil. This age was commonly listed as 10,000 years—an arbitrary number that used to correspond to the beginning of the Holocene Epoch (see timescale, Figure 1.2). The phrase "geologic context" does imply a certain level of antiquity to differentiate from historic objects, but nothing magically happens to an organism's remains once they reach the 10,000-year mark. Also, there is no requirement that an organism be extinct to be considered a fossil. Many of the fossil animals present in the Cenozoic fossil parks (titanotheres, oreodonts, entelodonts, etc.) and some of the plants are indeed extinct, but **extant** (living today) crocodiles and *Metasequoia* trees illustrate that extinction is not a requirement for something to be a fossil.

Misconceptions may be frustrating, but they might also provide excellent opportunities for an interpreter to help visitors make connections to deeper meanings behind the fossils.

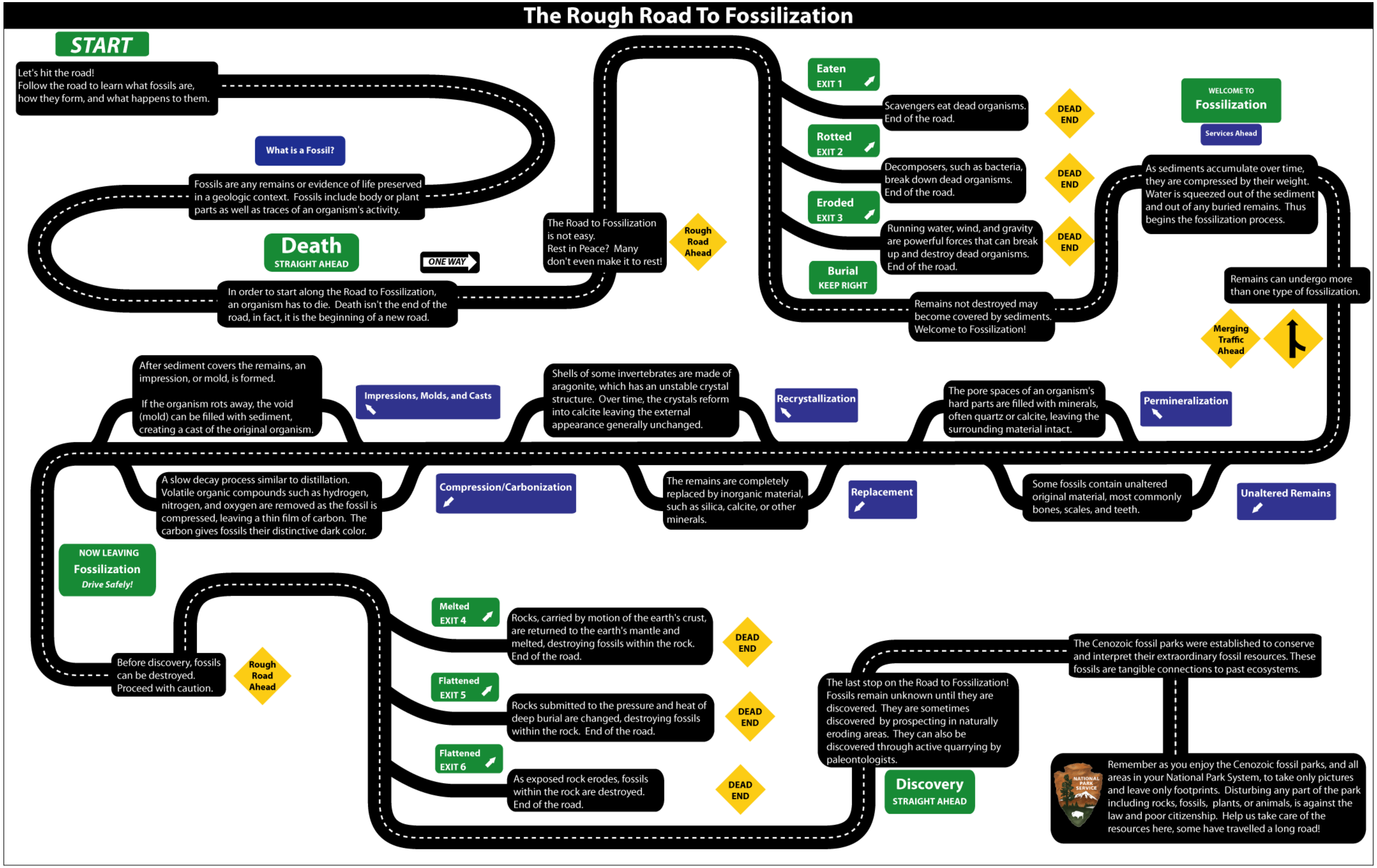


Figure 3.7. The Road to Fossilization is like the rocky, bumpy, sometimes impassable, two-track dirt roads that criss-cross western public lands. It is significantly more difficult than the 75 miles-per-hour interstate highways most of the visitors used while travelling to the Cenozoic fossil parks. (This diagram is adapted and updated from an exhibit the author developed at Fossil Butte NM.)

Figure 3.8. When an organism dies, it starts on the road to fossilization. Remains need to be buried rapidly to escape the ravages of scavengers, decay, and physical weathering. Will this pronghorn skeleton at Fossil Butte travel the entire road from death to discovery? Not likely, given the current erosive conditions at Fossil Butte NM and the other Cenozoic fossil parks. (Photo by Jason Kenworthy.)

Figure 3.9. Unaltered material keeps it real! Some of the fossil fish at Fossil Butte NM, including this "*Priscacara*" *liops* preserve original organic material from bones and scales, even after 52 million years of burial! (NPS photo.)

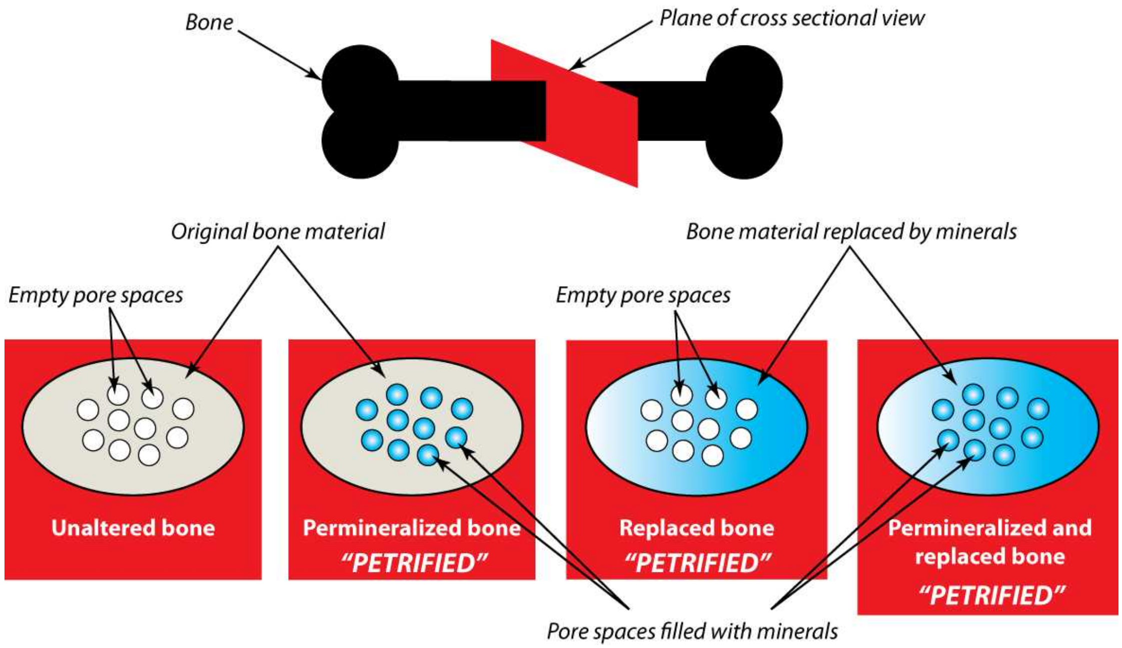


Figure 3.10. Turning to stone! These cross-sectional views of bone illustrate the differences between fossils that contain, from left to right, unaltered bone, permineralized bone, replaced bone, and permineralized and replaced bone. Fossils can be called "petrified" if they are permineralized, replaced, or both. Groundwater deposits minerals into the pore spaces of unaltered bone, and over time, can eventually replace all of the original organic bone material. The same process can occur for fossil wood, which like bone, has lots of pore spaces and canals.

Figure 3.11. This bone fragment from Hagerman Fossil Beds NM shows large mineral crystals filling the pore spaces where the bone's marrow used to be. There is no original material remaining in these bones: they have been completely replaced, hence the bone has been totally petrified. (Photo by Jason Kenworthy.)

Figure 3.12. The petrified redwood stumps at Florissant Fossil Beds NM are not only huge (Big Stump, pictured here, is 12 ft or 3.7 m in diameter!), they also preserve minute cellular detail. The trees were rapidly buried by lahars (volcanic mudflows) 34 million years ago. The silica in the lahars permineralized the stumps. (Photo by Jason Kenworthy.)

Figure 3.13. Fossils from the lake sediments of Florissant Fossil Beds NM, Fossil Butte NM, and John Day Fossil Beds NM (Bridge Creek flora) preserve high levels of detail via carbonization. From left to right: Butterfly *Prodryas persphone* (Florissant Fossil Beds NM; NPS photo); fish *"Priscacara" liops* (Fossil Butte NM; NPS photo); and leaves from the dawn redwood, *Metasequoia* (John Day Fossil Beds NM; Photo by Ellen Morris Bishop).

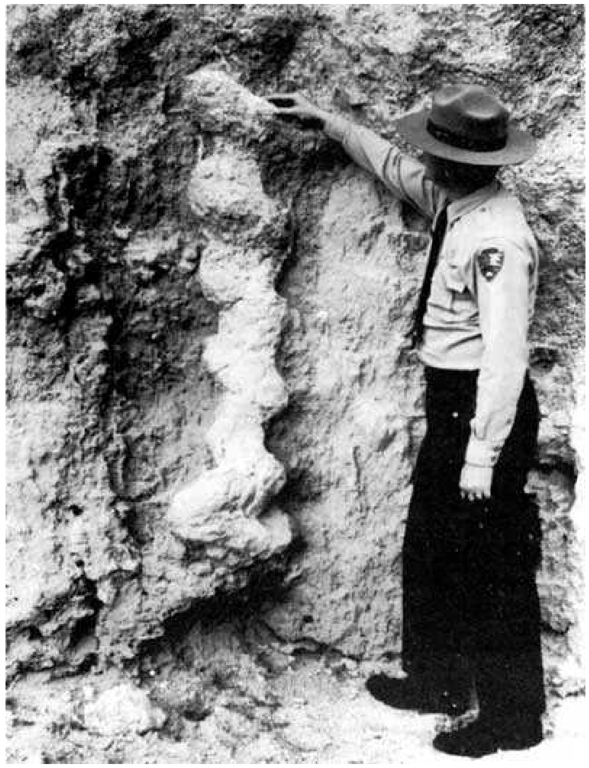


Figure 3.14. Distinctive, spiral-shaped burrows, called *Daemonelix* (“devil’s corkscrew”), of the ancient land beaver *Paleocastor* are found within Agate Fossil Beds NM. They are excellent examples of molds/casts as the original burrow was filled in with sediment and preserved as a trace fossil. (NPS photo.)

<u>Digging Deeper Box 3.9</u>. Unaltered Remains vs. "Petrified" Remains

The term **petrified** means "turned to stone" and is what most visitors expect when they think of fossils. This is appropriate given that most of the fossil bones and trees have indeed been "petrified." There are a few different ways remains can become petrified; they can be permineralized, replaced, or both. And in some cases, original material is preserved.

1. <u>Unaltered Remains</u>: Very rarely, some of an organism's remains (usually bones, teeth, or shells) are preserved without significant changes. Insects in amber and desiccated or mummified "Ice Age" mammals are some of the most spectacular examples, although ones not found in the Cenozoic fossil parks. Some of the fossil fish at Fossil Butte NM preserve pieces of original scales (Figure 3.9).

2. <u>Permineralization</u>: Rocks surrounding remains contain a variety of **minerals,** which may be dissolved by groundwater. As the groundwater saturates the remains, **ions** from the dissolved minerals can be redeposited in the empty pore spaces or canals of bone or wood (Figure 3.10). Volcanic ash is a large component of many of the floodplain and lake deposits in the Cenozoic fossil parks. Because volcanic ash is mostly composed of minerals rich in silica (for example, the mineral quartz is pure silica—SiO_2), many of the fossil bones in the Cenozoic fossil parks were permineralized with silica. Permineralization only fills in the pore spaces of organic material, leaving the wood or bone surrounding the pores intact. Because the pore spaces are filled with new minerals, this is a form of "petrification" (turning to stone) as the bones or woods are cemented together with these minerals. Many of the petrified wood samples in John Day Fossil Beds NM are permineralized.

3. <u>Replacement</u>: During the process of replacement, organic material is dissolved and minerals precipitated from the groundwater almost immediately take its place. The original material is thus replaced by minerals, instead of just filling in the empty pore spaces. This process leaves a representation of the organism as new mineral material—literally "turned to stone." Replacement is the process most visitors associate with fossilization, and the most common process in the vertebrate fossils of the Cenozoic fossil parks.

These three fossilization processes can also be thought of as steps in a process (Figure 3.10). For example, groundwater may start to infiltrate an <u>unaltered</u> bone or woody tree trunk, depositing minerals in the pore spaces, <u>permineralizing</u> it. If the process continues, the remaining organic material may be completely <u>replaced</u>, and the remains are then completely petrified (both permineralized and replaced) (Figure 3.11).

Digging Deeper Box 3.10*. *More Fossilization Processes

In addition to petrification, other processes can lead to the fossilization of plant and animal remains.

4. Recrystallization: Most invertebrate organisms that have shells make them out of calcium carbonate ($CaCO_3$), which comes in two varieties: aragonite and calcite. Shells are commonly made of aragonite, but this variety is unstable over long periods of time, particularly when buried. The aragonite can recrystallize—literally reform its crystal structure—to the more stable calcite. The original appearance of the fossil stays the same, just the microscopic crystal structure changes. This mode of fossilization is rare in the Cenozoic fossil parks as there are relatively few invertebrates with shells.

5. Compression/Carbonization: The basic building blocks of life are organic molecules composed primarily of molecules of the elements carbon, oxygen, hydrogen and nitrogen. Oxygen, hydrogen, and nitrogen can literally be squeezed out of remains as the organic material is buried and compressed. They escape as gasses leaving behind a residue of carbon. Carbon's dark color (graphite in pencils is carbon) stains the fossil a dramatic brown or black color (Figure 3.13) outlining where soft parts of the body once were. Fossils from the lake sediments of the Cenozoic fossil parks are commonly compressed and carbonized.

6. Molds/Casts/Impressions: A mold is an impression made by an organism's remains, particularly those with hard parts like shells, bones, or teeth, pressed into or surrounded by sediment. If the original material then decays or dissolves away, an empty space (mold) is formed. The mold might later be filled in with sediment creating a copy (cast) of the original remains. Imitating nature, many interpreters and visitors have made plaster casts of animal tracks in a similar fashion. Trace fossils in the Cenozoic fossil parks (burrows, dens, root casts, etc.) are also good examples of molds and casts (Figure 3.14).

Figure 3.15. The eroded landscapes of the Cenozoic fossil parks contain many fossils—so did the enormous amount of material eroded away to expose the layers visible today. Standing in a valley or near these layers is an effective way to have visitors visualize the volume of rocks (and fossils) that are *not* there—eroded away. Connecting layers across a valley at an overlook or along a trail is one effective technique. The flat layers at Badlands NP (left) facilitate this connection. The Fossil Hills of Agate Fossil Beds NM (right) stand tall as erosional remnants on the prairie. (Photos by Jason Kenworthy.)

Figure 3.16. Discovery is the last stop on the road to fossilization. Left: Quarrying at Badlands NP "Big Pig Dig" (an Oligocene waterhole with a concentration of fossils) exposes new specimens more rapidly than natural erosive processes. (Photo by Jason Kenworthy.) Right: Getting up close and personal with the rocks, prospecting paleontologists look for fossils exposed by erosion at John Day Fossil Beds NM. (Photo by Robert J. Lillie.)

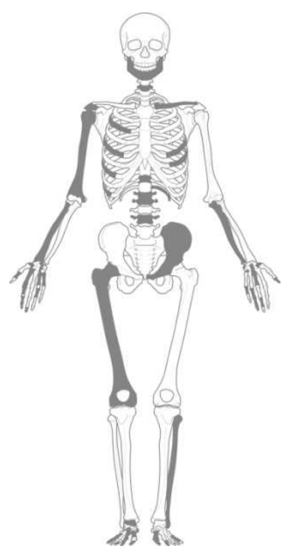


Figure 3.17. 300,000,000 x 206 yields only 62! According to one estimate, only one bone in a *billion* is preserved as a fossil. Using this ratio, the entire fossil record of the nearly 300,000,000 people living in the United States today (each with 206 bones) would be only 62 bones (shaded on the skeleton to the left), less than one-third of *one* complete human skeleton! Analogies like this help visitors appreciate the uniqueness of each fossil.

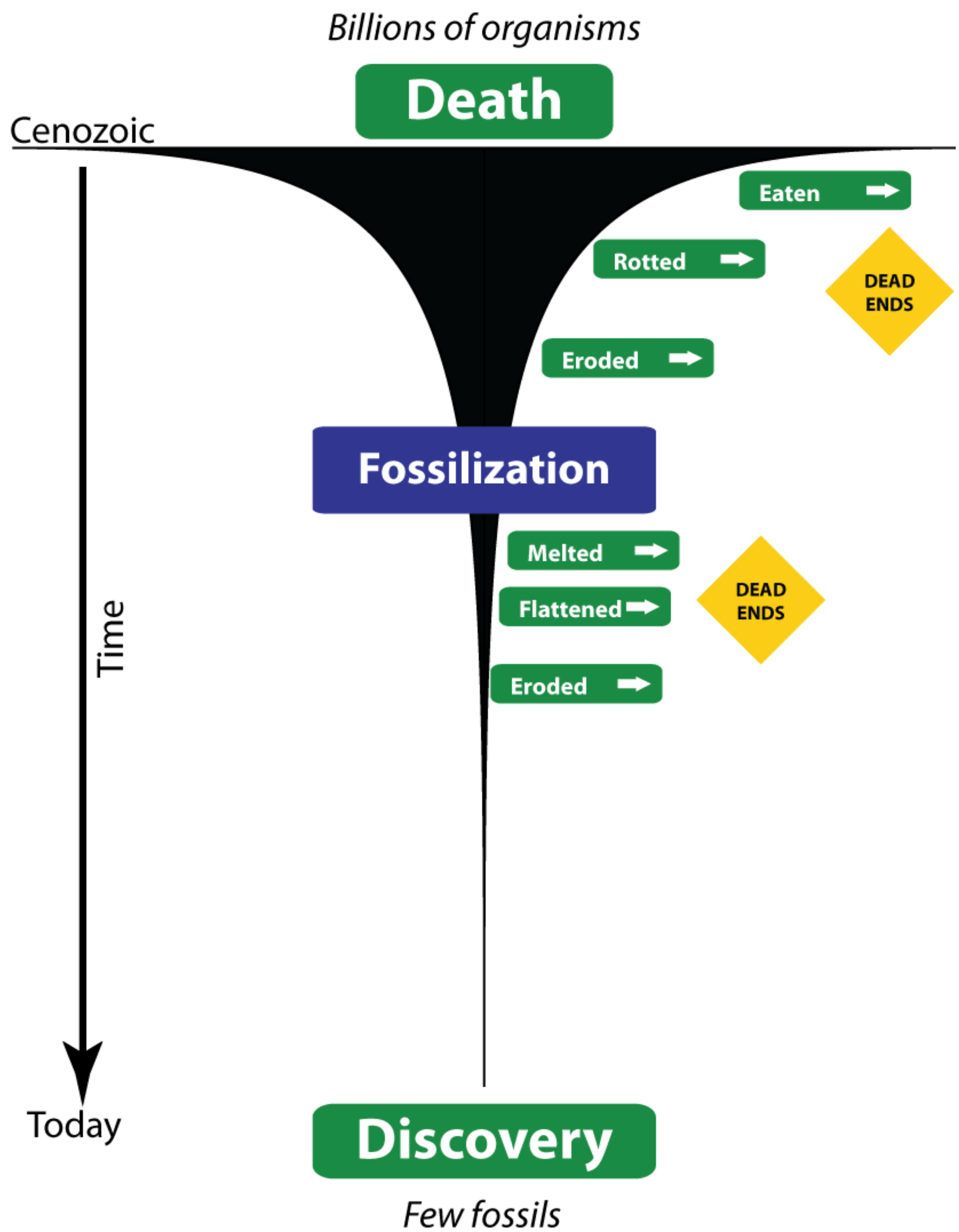


Figure 3.18. The road to fossilization is not an easy road. As shown above, while every organism eventually travels on the road to fossilization—beginning as soon as they die—very few travel the entire road and are discovered by paleontologists in the Cenozoic fossil parks. When interacting with visitors, interpreters can spread their arms wide to represent the total number of organisms that used to live in the park, and bring their arms in for each of the exits, until with discovery, you can illustrate that just a small fraction (hold the thumb and index finger together to represent less than the width of a hair) are actually discovered.

***Digging Deeper Box 3.11*. Take only pictures and leave only footprints.**

Fossils are non-renewable resources. There are no more *Moropus* wandering northwest Nebraska near Agate Fossil Beds NM. Interpretation should include a resource management and NPS stewardship mission message encouraging visitors to be proactive at the park. Keep a positive perspective on these special places and the rangers and visitors who work and recreate there!

While mentioning the regulations, empower the visitor with something they *can* do rather than focusing on what they *cannot* do. Remind visitors to report fossil discoveries to park staff. Have visitors "bring the ranger to the fossil" rather than "bringing the fossil to a ranger" (although a digital photograph works well). This conserves the context of the fossil and preserves the sense of discovery for the next visitor so that they too can share that feeling. Badlands NP, for example, has a form visitors fill out to report fossil discoveries, which are subsequently investigated by the paleontology field crew. One such visitor report led to the discovery and 15 year (1993-2008) excavation of an Oligocene water hole deposit at the Big Pig Dig near Conata Picnic Area.

Generally only well-preserved, identifiable, rare, complete, or otherwise significant fossils are collected. Many fossil resources are managed *in situ* (left in place) because the NPS has a mandate to conserve natural processes, which includes erosion. And while visitors are not allowed to dig in the parks themselves, they are usually excited to hear that field crews are still working in the park and making new discoveries.

Interpretive programs that include real, touchable fossils; demonstrations of quarrying or preparation techniques; or actual participation in an excavation provide a very tangible connection between visitors and the fossils and an opportunity to discuss not only the science of paleontology, but also the stewardship mission of the National Park Service.

Chapters 4–6

The paleoecosystems of the Cenozoic fossil parks evolve

The Cenozoic was a time of change—evolution—in landscape, climate, and organisms. There is much evidence of this change preserved and archived in the Cenozoic fossil parks. The active geologic landscape of western North America evolved with rising mountains and erupting volcanoes. Global climate changed from a global “greenhouse” with no ice sheets on either pole to a global “icehouse” poised for great advances of ice during the Pleistocene “ice ages.” Life evolved on this changing stage as mammals expanded and diversified following the extinction of dinosaurs at the end of the Cretaceous Period 65.5 million years ago.

The National Park Service utilizes an ecosystem approach to resource stewardship and interpretation. As defined in the National Park Service Management Policies (2006), ecosystems are “systems formed by the interaction of a community of organisms with their physical and biological environment, considered as a unit.” The “system” portion of the term reinforces the interconnected nature of living things and their physical environment. The rock layers of each Cenozoic fossil park are part of the present-day ecosystem that preserve components of fossilized ecosystems. Such paleoecosystems are diverse assemblages of fossil plants and animals that *lived together* in communities, interacting with each other and their environments.

An ecosystem approach can yield effective interpretation of present park ecosystems, because individual plants and animals are presented in their broader context. The fossil parks, by virtue of their extraordinary preservation and diversity of fossil resources, facilitate interpretation of entire paleoecosystems, not just individual fossils. Fossil remains (organisms) and geologic context (landscape and climate) are the components that together form paleoecosystems. Plants and animals in a modern ecosystem represent adaptations to a particular range of climate conditions. A park’s paleoecosystems can be compared to the park’s modern ecosystem to tell a story of changing climate. This manual reveals how the evolution of paleoecosystems throughout the Cenozoic can be related to visitors via thematic interpretation that connects observations from all the fossil parks.

The physical landscape, climate, and organisms are the fundamental components of ecosystems. Three big ideas can be used to tell the story of change represented by the paleoecosystems preserved in the Cenozoic fossil parks and can be used as interpretive themes:

1. The active geologic landscape of the American West, including rising mountains and erupting volcanoes, developed and preserved the paleoecosystems of the Cenozoic fossil parks (Chapter 4).

2. Global climate change contributed to the transformation of Cenozoic fossil park ecosystems from near-tropical forests and lakes on a “greenhouse” Earth to cooler and drier woodlands, savannahs, and grasslands on an “icehouse” Earth (Chapter 5).

3. The Cenozoic fossil parks preserve fossils of horses that migrated, adapted, and went extinct as ecosystems changed (Chapter 6).

In other words, the active geologic processes of the American West provided the sediment needed to bury, preserve, and accurately determine the ages of paleoecosystems. This time of increased preservation potential coincided with one of Earth’s few great climatic shifts, and the amazing evolution of mammals in a world no longer populated by dominant dinosaurs. Thus, the stage was set to record the Cenozoic story of the American West—what a remarkable story it is!

Chapter 4

Rising mountains and erupting volcanoes shaped and preserved Cenozoic fossil park paleoecosystems

Go outside your visitor center and take a look around. The physical landscapes visible within the fossil parks, be they dramatic eroded bluffs or more subtle low hills, are the foundations of today's ecosystems. They also contain fossil evidence of earlier paleoecosystems. Most of the rocks in the Cenozoic fossil parks are sedimentary **rocks**: rocks composed of fragments of other rocks that were eroded, transported, and deposited. So where did all these paleoecosystem-entombing rock fragments come from? The rugged landscape of the American West (Figure 1.1) results from plate tectonic forces that construct landforms (**topography**)—in effect making highlands and lowlands. Gravity transports eroded rock fragments (sediment) from highland areas to lowlands, or basins. The paleoecosystems of the Cenozoic fossil parks evolved as the landscape of the West changed dramatically (Figure 4.1), driven in large part by a **subduction zone** where tectonic plates of the Earth's crust were colliding off the west coast of North America.

The landscape of western North America has changed considerably since the time of the dinosaurs ended 65.5 million years and a continental sea bisected the continent (Box 4.1, Figures 4.2 and 4.3). During the Cenozoic, the Rocky Mountains continued to rise, ranges of volcanoes erupted near the west coast, the continent grew westward as pieces of ocean floor and continental fragments were added to its edge, and the Basin and Range province began to pull apart. Unfathomable amounts of volcanic material flooded the landscape as the Yellowstone hotspot surfaced. Volcanoes from many sources erupted over the landscape of each of the Cenozoic fossil parks. Amidst this geologic upheaval, the Cenozoic fossil parks were areas of deposition from sediment eroded from this ever-changing landscape. Layer upon layer of sediment—crucial for entombing animals and plants, the evidence of these paleoecosystems—were deposited. These layers later became the sedimentary rocks now visible in the fossil parks. Dateable volcanic ash layers (Chapter 3) provided page numbers (ages) to the stories written in the sedimentary rocks and fossils of the parks. The evolving landscape of the American West thus shaped and preserved Cenozoic fossil park paleoecosystems.

Depositional environments bury fossils and ecosystems.

Fossilization (Chapter 3) requires burial in a place where sediment is accumulating—a **depositional environment**. Within the Cenozoic fossil parks, there are four primary depositional environments: floodplain in a river basin (**fluvial**), lake bottom (**lacustrine**), volcanic mudflows (**lahars**), and wind-blown (**eolian**) settings. Agate Fossil Beds NM, Badlands NP, Hagerman Fossil Beds NM, and John Day Fossil Beds NM (Turtle Cove, Kimberly, Haystack Valley, Mascall, and Rattlesnake **strata**) preserve fossils from fluvial environments. Fossil Butte NM, Florissant Fossil Beds

NM, and John Day Fossil Beds NM (Bridge Creek and Mascall strata) preserve fossils from lacustrine environments. The redwood stumps at Florissant Fossil Beds NM and some of the plant fossils from the Clarno assemblage at John Day Fossil Beds NM are preserved in lahars. The Harrison Formation at Agate Fossil Beds NM and part of the Brule Formation of Badlands NP contain extensive eolian deposits. The reconstructions in Chapter 1 illustrate these different depositional environments.

Evidence for these depositional environments is preserved within **sedimentary rocks**. There are two main types of sedimentary rocks, both of which are found in the Cenozoic fossil parks: clastic and chemical. **Clastic sedimentary rocks**, the most common in the Cenozoic fossil parks, are the products of weathering, erosion, transportation, and deposition of rock fragments (**clasts**). A dump truck picking up and transporting bits of rock, depositing them elsewhere is one analogy (Figure 4.4). The dump truck empties its bed more quickly the higher the bed is raised. Likewise, areas that are actively uplifting or have high topography erode rapidly, supplying sediment to the depositional environments in the adjacent lowlands. Moving wind and water picks up and transports the clasts and deposits them elsewhere when the wind or water no longer has the energy to move them. Thus sedimentary rocks provide clues toward the past depositional environment and the geologic foundation of paleoecosystems. Higher-energy depositional environments, such as fast-moving streams, leave behind larger (heavier) clasts while transporting smaller (lighter) clasts. The large clasts found in **conglomerates** and **sandstones** indicate higher-energy depositional environments. Where water is moving very slow (or not at all) such as in lakes, the water cannot transport even the smallest clasts and they are deposited. The small clasts of **siltstones** and **claystones** indicate quieter environments such as lakes or floodplains. Sedimentary layers with small clasts are excellent for preserving intricate fossil details. Lacustrine paleoecosystems thus contain some of the best preserved and most complete fossils in the Cenozoic fossil parks (Box 4.2). Clastic sedimentary rocks are named after the size of clasts (Figure. 4.5). When volcanic material (such as ash or weathered volcanic rocks) are incorporated as clasts, the rocks are called **volcaniclastic**. Because so many volcanoes were erupting during the time periods preserved at the fossil parks, many of the rocks at John Day Fossil Beds NM, Badlands NP, Florissant Fossil Beds NM, and Agate Fossil Beds NM contain a high percentage of volcaniclastics.

Chemical sedimentary rocks form when **ions** (microscopic "bits" of rock dissolved during **chemical weathering**) precipitate out of water. The calcium carbonate (or calcite: $CaCO_3$)-rich shales of Fossil Butte NM are an example of chemical sedimentary rocks. Once sedimentary rocks are formed and re-exposed the cycle of erosion, transportation and deposition begins again (Box 4.3, Figure 4.6).

As sediment accumulates in the various depositional environments, remains of animals or plants can be buried as well. A very small sample of the plants and animals in a given ecosystem eventually become fossils (Chapter 3). As the layers build up over time, water is driven out and the sediment compacts into rock. Minerals dissolved in water (such as quartz and calcium carbonate) might seep into the pore spaces between the sediment grains and come out of solution (precipitate from the water), cementing the rock together. If this sounds a lot like fossilization (Chapter 3), it should. The same processes that turn remains into fossils—burial, compaction, cementation—turn sediment into rock.

Plate tectonic processes formed the mountains and fueled the volcanoes that shaped and preserved the depositional environments of the Cenozoic fossil parks.

Each of the Cenozoic fossil parks contains a depositional environment associated with significant events of the Cenozoic geologic history of the American West. Rising mountains and erupting volcanoes shaped the landscape following the retreat of a vast continental sea (Box 4.1, Figures 4.2 and 4.3). The Rocky Mountains continued to rise along **fold and thrust belts** and **basement uplifts**. Successive volcanic ranges formed along the west coast. The continent expanded westward as oceanic islands and continental fragments came crashing in. The Basin and Range Province began pulling apart. The “hotspot” that now fuels Yellowstone’s geysers surfaced and flooded the landscape with lava. All the while volcanoes erupted ash and other materials over the landscape of each Cenozoic fossil park.

Plate tectonic (from the Greek *tekton*, meaning “builder”) processes drove these landscape changes. For more on plate tectonics, Lillie (2005) provides an introduction and detailed discussion of plate tectonics using examples from throughout the National Park System. He also includes a variety of interpretive techniques to engage visitors with plate tectonic processes. This section presents an overview of how plate tectonic processes contributed to the development and preservation of the Cenozoic fossil parks’ paleoecosystems. Although many different processes have impacted the Cenozoic fossil parks, one—**subduction**—has been particularly pervasive for the duration of the Cenozoic and continues today. For more than 200 million years, plates under the Pacific Ocean have been subducting beneath the North American continent (Box 4.4, Figure 4.7). Because two plates collide together at a subduction zone, there are tremendous compressive forces which crumple the landscape and form mountains. Subduction built the Rocky Mountains, fueled coastal volcanoes, and added land onto the edge of North America during the Cenozoic Era.

<u>Construction of the Rocky Mountains (Fossil Butte NM, Badlands NP, Florissant Fossil Beds NM, and Agate Fossil Beds NM)</u>

The Rocky Mountains (Figure 4.8) are icons of the American West. They were under construction though multiple mountain-building events (called **orogenies**) beginning about 170 million years ago, until about 40 million years ago. Since plate tectonics became the foundation for modern geology in the 1960s, one of the great questions geologists have attempted to answer is how did the Rocky Mountains form so far from the coast and the subduction zone?

The answer is thought to lie in the angle of the subducting plate. When the angle of subduction was steep (Figure 4.9), the subducting plate descended deep enough to fuel volcanoes along the coastline—a "typical" subduction zone, like today's Cascadia Subduction Zone. During these times, the hard "**basement**" rock (composed of very deep and old metamorphosed and previously molten **igneous rocks**) is generally not deformed. However, relatively soft sedimentary rocks overlying them are compressed and crumpled, folded and shoved eastward along shallow-angle **thrust faults,** much like snow plows scraping soft, deformable snow on a hard blacktop road. These fold and thrust belts are found in parts of Montana, Wyoming, and Utah (Figure 4.10). Fossil Lake filled a basin on the eastern edge of a series of these fold and thrust belts, depositing the sediments now exposed within Fossil Butte NM (McGrew and Casilliano, 1975). This style of Rocky Mountain building was common between about 140 and 50 million years ago and during the Sevier Orogeny.

A much shallower angle of subduction (Figure 4.11) may have contributed to the uplift of ancient basement rocks far from the edge of the continent. Uplift of this type occurs along steep-angle faults that lift deep basement rocks toward the surface. As the basement rocks are pushed to the surface, overlying sedimentary rocks are eroded away, becoming clasts for new rocks deposited in adjacent basins, such as the extensive **foreland basin** east of the Rocky Mountains (Figure 4.8). This style of Rocky Mountain building is called "Laramide uplifts" and commonly occurred from about 80 to 40 million years ago, during the last of the major Rocky Mountain building events (the Laramide Orogeny). Uplifted and exposed blocks of Precambrian rocks are within or near three Cenozoic fossil parks (Figure 4.10). The Pikes Peak Granite found within Florissant Fossil Beds NM is approximately 1,080 million years old (Wobus, 1994). In the core of the Black Hills, the Harney Peak Granite—carved into Mt. Rushmore's presidential portraits west of Badlands NP—is 1,710 million years old (Redden and others, 1990). The core of the Hartville Uplift of the Laramie Mountains west of Agate Fossil Beds NM contains igneous rocks between 1,720 million and more than 2,500 million years old (Day and others, 1999; Sims and Day, 1999).

Erosion attacked these mountains. Paleoecosystems located on the eroding flanks of Pikes Peak had little chance of long-term preservation. But lahars dammed a mountain stream, forming a lake that preserved the paleoecosystems of Florissant Fossil Beds NM, one of many significant contributions from volcanoes to the preservation of Cenozoic fossil park paleoecosystems (Box 4.5). Eroding mountains deposited enormous quantities in adjacent basins. The foreland basin on the **continental platform** of central North America received vast quantities of sediment. Badlands NP and Agate Fossil Beds NM are located at depressed regions (basins) on the continental platform (Figure 4.8). The

Cenozoic sedimentary rocks of Badlands NP are composed of fragments of rocks eroded from the uplifted Black Hills to the west. Likewise, Agate Fossil Beds NM contains sediment eroded from the Hartville Uplift of the Laramie Mountains. Not all of the sediment at these two parks is Rocky Mountain fragments—a large proportion is volcaniclastic sediment with volcanic ash mixed in from volcanoes erupting in Nevada and Utah (Hunt, 1985, 1990; Larson and Evanoff, 1998). Although the events constructing the foundation of the Rocky Mountains were completed during the Eocene, their current elevations and shapes took tens of millions of years to form through complex interactions of climate change, erosion, and uplift. Recent studies including the plant fossils of Florissant Fossil Beds NM suggest the Rocky Mountains might have achieved elevations similar to today's, or even higher during the early Cenozoic (Box 4.6).

<u>Subduction zone volcanoes erupted along the West Coast (John Day Fossil Beds NM)</u>

During the Mesozoic Era, a range of subduction zone volcanoes spanned much of North America's western edge as a massive oceanic plate, called the Farallon Plate, subducted beneath the continent. The Sierra Nevadas, including Yosemite National Park, are evidence of this ancient chain of volcanoes (Dunham, 2009). By the Cenozoic Era, most of the Farallon Plate had subducted. The Juan de Fuca and Cocos plates were all that remained, as the jagged trailing edge of the larger plate. These two smaller plates continue to subduct beneath the Pacific Northwest and Central America, respectively (Figure 4.12). Volcanism related to the subduction of the Farallon and Juan de Fuca plates helped form and preserve the paleoecosystems of John Day Fossil Beds NM.

The Clarno volcanoes were the first of Oregon's subduction zone ranges, erupting between 55 and 40 million years ago. Ecosystems on the flanks and adjacent lowlands of these volcanoes were repeatedly overrun by lahars. Streams transported erupted materials and eroded fragments of volcanic rock. This volcanic turmoil and rapid burial preserved paleoecosystems such as those found in the 44 million-year-old Clarno Nut Beds (Manchester, 1994). During the late Eocene, the most recent accreted terranes and seamounts (termed the "Siletz Terrane") clogged the subduction zone that fueled the Clarno volcanoes. By about 30 million years ago, the subduction zone (now called the Cascadia Subduction Zone), was again active farther to the west. These ancestral, or Western Cascades, spewed volcanic ash in dozens of eruptions, supplying immense amounts of volcaniclastic sediment that would preserve the paleoecosystems of the John Day Formation during the Oligocene and Miocene (Hunt and Stepleton, 2004). Eruptions from the Western Cascades continued through much of the Miocene. Today's High Cascade Volcanoes, including Mt. Rainier, Mt. Hood, the Three Sisters, and Mt. Shasta, began to develop during the Pliocene around 5 million years ago. The Cascadia Subduction Zone is still active today, fueling volcanoes in NPS units such as Crater Lake, Mount Rainier, and Lassen Volcanic national parks and Mount St. Helens National Volcanic Monument (a U.S. Forest Service site).

Westward expansion enlarged the North American continent (John Day Fossil Beds NM)

Westward expansion, a hallmark of United States policy in the 1800s, is not a new thing. Geologically, "westward expansion" has been occurring for more than 200 million years (thanks to Lisa Fay, NPS paleontology intern, for this analogy)! As oceanic crust subducted beneath the North American continent, microcontinents, volcanic island chains (similar to Hawaii) and seamounts riding along with the crust "crashed" in and, unable to subduct, were deformed and attached to the western coastline. Such added lands form the bedrock over much of the North American **Cordillera** and are called **accreted terranes** (Coney and others, 1980) (Figure 4.13). In this manner, North America expanded westward during the late Mesozoic and early Cenozoic eras. A similar process occurs along a grocery store check-out conveyor. Groceries on the belt are spread out, steadily moving closer and closer to the end of the conveyor (subduction zone). When the belt "subducts" into the counter, the groceries pile up on each other (Figure 4.14).

John Day Fossil Beds NM contains evidence of the continent's westward expansion. During the middle of the Mesozoic Era, the west coast of North America was near the Idaho-Oregon border. Accreted terranes in the Blue Mountains moved the coast westward to about Mitchell, Oregon (site of the Painted Hills unit). The Goose Rock conglomerate, more than 110 million years old (Aguirre and Fisk, 1987), contains rounded cobbles derived from the Blue Mountains transported westward on their way to the ocean. The 44 million-year-old Clarno forests were only about 60 miles (100 km) east of the coast (Manchester, 1994). Today, Clarno fossils are in central Oregon, about 180 miles (290 km) east of the Pacific Ocean. Seamounts off the coast were the last terranes added to the continent; they were in place by the end of the Eocene (34 million years ago). The Coastal Ranges of Washington, Oregon, and northern California represent material scraped off the descending plate, annexed onto North America, and subsequently uplifted and deformed into low, non-volcanic mountains, such as those in Olympic NP (Washington), Oregon Caves NM (Oregon), and Redwood National and State Parks (California) (Lillie, 2005).

Volcanic materials blanketed the Cenozoic fossil parks (Fossil Butte NM, John Day Fossil Beds NM, Badlands NP, Florissant Fossil Beds NM, Agate Fossil Beds NM, Hagerman Fossil Beds NM)

The geologic evolution of the American West was continuously punctuated by volcanic eruptions from a variety of sources. Today active volcanoes are found in the continental United States along the Cascade Range; the Basin and Range Province and Rio Grande Rift; Yellowstone Hotspot; and Eastern Snake River Plain. Between 52 and 3.2 million years ago, volcanoes erupted from multiple sources, disgorging immense amounts of volcanic ash, lava, and other erupted materials onto the landscape. These materials played a crucial role in the preservation and understanding of the Cenozoic fossil park paleoecosystems (Box 4.5).

The 52 million-year-old ash layers from Fossil Butte NM likely erupted from the Absaroka Range located near within today's Yellowstone NP but were not associated with the hotspot currently underneath the park) (Smith and others, 2003). Volcanoes erupting in Utah or Nevada supplied much of the volcanic material in the 37 to 26 million-year-old Chadron, Brule, and Sharps formation of Badlands NP, including the Rockyford Ash (Larson and Evanoff, 1998). At Florissant Fossil Beds NM, lahars from the Thirtynine Mile volcanic field buried the *Sequoia*-like stumps and later dammed streams to form Lake Florissant 34 million years ago (Evanoff and others, 2001). Additional volcanic material found in Lake Florissant's deposits may have originated from a variety of sources such as the Mt. Aetna caldera southwest of the park, the Grizzly Peak caldera west of the park, or another still undiscovered source (Evanoff and others, 2001). These volcanoes were part of a widespread spate of volcanism in roughly the same areas as the Larmide Uplifts, where the fractured bedrock may have provided conduits for molten materials after the close of the Larmide Orogeny. This spate of volcanism has been termed the "Mid-Tertiary Ignimbrite Flare-Up" referring to the particularly explosive type of eruptions common during that time.

Volcanic centers in Utah, Nevada, are likely sources of 23 to 19 million-year-old volcanic ash in Agate Fossil Beds NM (Hunt, 1985, 1990). Nearby eruptions of basalt flowed into what is now Hagerman Fossil Beds NM. A more distant supervolcano eruption associated with the Yellowstone Hotspot deposited the 3.7 million-year-old Peters Gulch Ash in Hagerman Fossil Beds NM (McDonald and others, 1996). In addition to the Clarno and Cascade volcanoes described above, John Day Fossil Beds NM received volcanic materials from some highly explosive sources. The 7.05 million-year-old Rattlesnake Ash Flow Tuff and Mascall Tuff (15.8 million years old) erupted from vents the Harney Basin about 90 miles (145 miles) south of the visitor center (Streck and Ferns, 2004; Streck and others, 1999). In one cataclysmic eruption, the Rattlesnake Tuff eruption ejected 67 cubic miles of material (280 cubic kilometers) over most of central Oregon (Streck and others, 1999). The caldera eruptions that blanketed Florissant Fossil Beds NM and Hagerman Fossil Beds NM packed similar explosive punch. For comparison the devastating 1991 eruption of Mt. Pinatubo—the second largest of the 1900s—produced just 2.4 cubic miles (10 cubic kilometers) of ash and other volcanic materials (Paladio-Melosantos and others, 1996). Closer to home in North America, the May 18, 1980 eruption of Mt. St. Helens produced just one-tenth the erupted material of Pinatubo—0.26 cubic miles (1.1 cubic km)—or about the volume of a football stadium (Sarna-Wojcicki and others, 1981).

<u>The Basin and Range stretches out (John Day Fossil Beds NM and Hagerman Fossil Beds NM)</u>

Most of the tectonic processes mentioned above were driven by the subduction zone along the west coast of the continent, where two plates are converging and colliding with each other. About 20 million years ago, the opposite process began and continues today in southern Oregon, Nevada, western

Utah, and southwestern Idaho—an area called the Basin and Range province (Figure 4.8). Rather than plates coming together and colliding, in the Basin and Range the North American plate is being pulled apart. This tectonic pulling-apart (called "rifting") leads to a distinct landscape scarred by faults where large blocks of Earth's crust move downward, forming valleys (basins) between tilted blocks of Earth's crust that remain high, forming mountain ranges. The parallel basins and ranges of this province are easy to spot on any map (Figure 4.8). As might be expected, earthquakes and volcanoes are side effects of the crust being ripped apart. Some of the volcanism associated with the Basin and Range affected the paleoecosystems of John Day Fossil Beds NM and Hagerman Fossil Beds NM although neither park is located within the Basin and Range province. For example, eruptions like those that produced the Rattlesnake Ash Flow Tuff mentioned in the previous section, are at least partially influenced by Basin and Range rifting. Basalt volcanism along the Snake River Plain in Idaho is due to a combination of Yellowstone hotspot volcanism and Basin and Range rifting. Craters of the Moon NM and Preserve (about 100 miles [160 km] northeast of Hagerman Fossil Beds NM) interprets the resultant "weird and scenic landscape" (Truitt, 2006). The basalt flows interspersed within the sediments of Hagerman Fossil Beds NM may likewise be associated with Basin and Range volcanoes.

<u>The Yellowstone hotspot surfaced (John Day Fossil Beds NM and Hagerman Fossil Beds NM)</u>

Visitors entering John Day Fossil Beds NM Sheep Rock unit from the south, pass through nearly 1,000 ft (300 m) of impressive, 16 million-year-old black **basalt** columns in Picture Gorge (Figure 1.11). The 17 lava flows visible in the gorge represent but a tiny fraction of the Columbia River Basalt Group. The Columbia River Basalts comprise an immense amount of basalt that spilled out from huge cracks over the Oregon, Washington, and Idaho landscapes during the Miocene. The eruptions took place from about 17 to 6 million years ago, although the vast majority of the lava erupted by about 14 million years ago. Together with the 17 to 15 million-year-old Steens Basalts from southeastern Oregon, enough basalt erupted to blanket the continental United States to a depth of nearly 100 feet (30 m)! Although long debated and still being investigated, the source for such an extraordinary amount of lava is likely the surfacing of the Yellowstone **hotspot** (Hooper and others, 2007). Hotspots, for reasons not yet fully understood, originate deep in Earth's mantle and channel enormous amounts of molten material to Earth's surface. In the United States, Yellowstone's geothermal features and the volcanoes of Hawaii are fueled by hotspots.

As the North American continent travelled southwest over the stationary hotspot during the past 17 million years, volcanic eruptions occurred in a track to the northeast across the Eastern Snake River Plain—interpreted at Craters of the Moon National Monument and Preserve (Truitt, 2006) (Figure 4.15). The hotspot now fuels the geothermal wonders of Yellowstone National Park. The passage of the plate over the hotspot bowed the landscape upward (Beranek and others, 2006). Along the flank of this bulge, the Western Snake River Plain down-dropped along faults. Visitors might recognize a similar process from moles tunneling just beneath the surface of their yard, leaving behind a disturbed landscape. Beginning about 11 million years ago, lakes occupied this basin (collectively referred to as “Lake Idaho”). The 4 to 3 million-year-old paleoecosystems of Hagerman Fossil Beds NM were located within and alongside one of these lakes.

Interpreting the Rising Mountains and Erupting Volcanoes of the Cenozoic fossil parks

Without heaping helpings of sediment to bury plants and animals, there would be no Cenozoic fossil parks! The rocks that surround each fossil, make up the bluffs, and provide the framework for the modern ecosystems of the park had to come from somewhere. The story of fossil preservation is thus intimately tied to the active geology of the American West during the Cenozoic Era. As mountains were built and volcanoes erupted, the Cenozoic fossil parks were areas of deposition. Today they are eroding away. Trying to include the entire story of Cenozoic landscape evolution is probably a bit much for one interpretive program. Framing the geologic processes (like the MVP—volcanism [Box 4.5]) in terms of fossil preservation, provides a link between the tangible rocks and fossils of each park and the intangible visualization of past geologic processes. Such interpretation also provides an opportunity to discuss fossilization processes along the road to fossilization (Chapter 3). The Cenozoic fossil parks are not just home to spectacular fossils, they are also home to spectacular scenery. For visitors from the East Coast (like myself) or Midwest, the stark, still-forming and “young” landscapes of the American West are a particularly powerful tangible because they are so different than the rounded, low hills, and plains typical of the “old” landscapes of the East. As we will see in Chapter 5, the evolving landscape of the American West influenced the climate of the parks. The varied landscapes of the West also provided a variety of habitats that influenced the family history of the horse (Chapter 6).

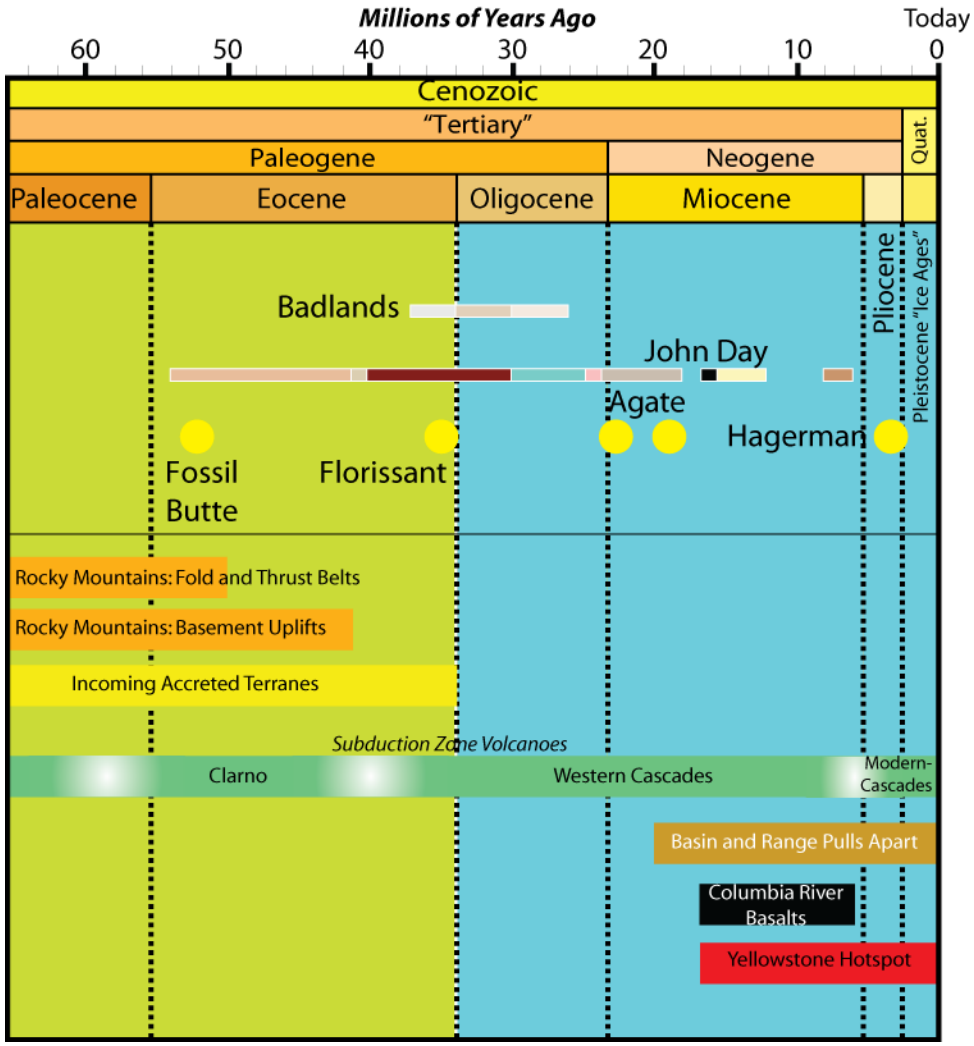


Figure 4.1. Tectonic events shaped the paleoecosystems of the Cenozoic fossil parks. The approximate time span of tectonic events described in the text are shown here along with the time spanned by paleoecosystems at each of the parks. "Quat." = Quaternary Period.

Digging Deeper Box 4.1. ***When did that inland sea inundate North America?***

Many visitors have heard about a “vast inland sea” that covered most of North America. This inland sea existed during the Mesozoic Era, when the West Coast ran through what is now the middle of Oregon. John Day Fossil Beds NM and Badlands NP contain rocks from this time period. The Goose Rock Conglomerate within John Day Fossil Beds NM was deposited about 90 million years ago in a mountain stream close to the ancient coast line, which was near Mitchell, Oregon (Painted Hills). To the east, the interior of the continent was under water as global sea level rose, flooding a large basin (called a **foreland basin**) on the eastern edge of the rising Rocky Mountains. The seaway, called the Western Interior Seaway (or Cretaceous Interior Sea), connected the Gulf of Mexico to the Arctic Ocean, separating the continent for much of the middle and late Cretaceous (Figure 4.2). The Pierre Shale and Fox Hills Formation within Badlands NP contain fossil evidence of **mosasaurs**, **ammonites**, and Volkswagen Beetle-sized turtles that populated this sea. By the beginning of the Cenozoic Era, 65.5 million years ago, rising mountains on the west and retreating seas worldwide began to drain the seaway (Figure. 4.3). As the seafloor sediments were exposed during uplift and erosion, lush tropical forests grew on the soils that formed (Retallack, 1983). The Yellow Mounds of Badlands NP are evidence of this ancient forest and its soils.

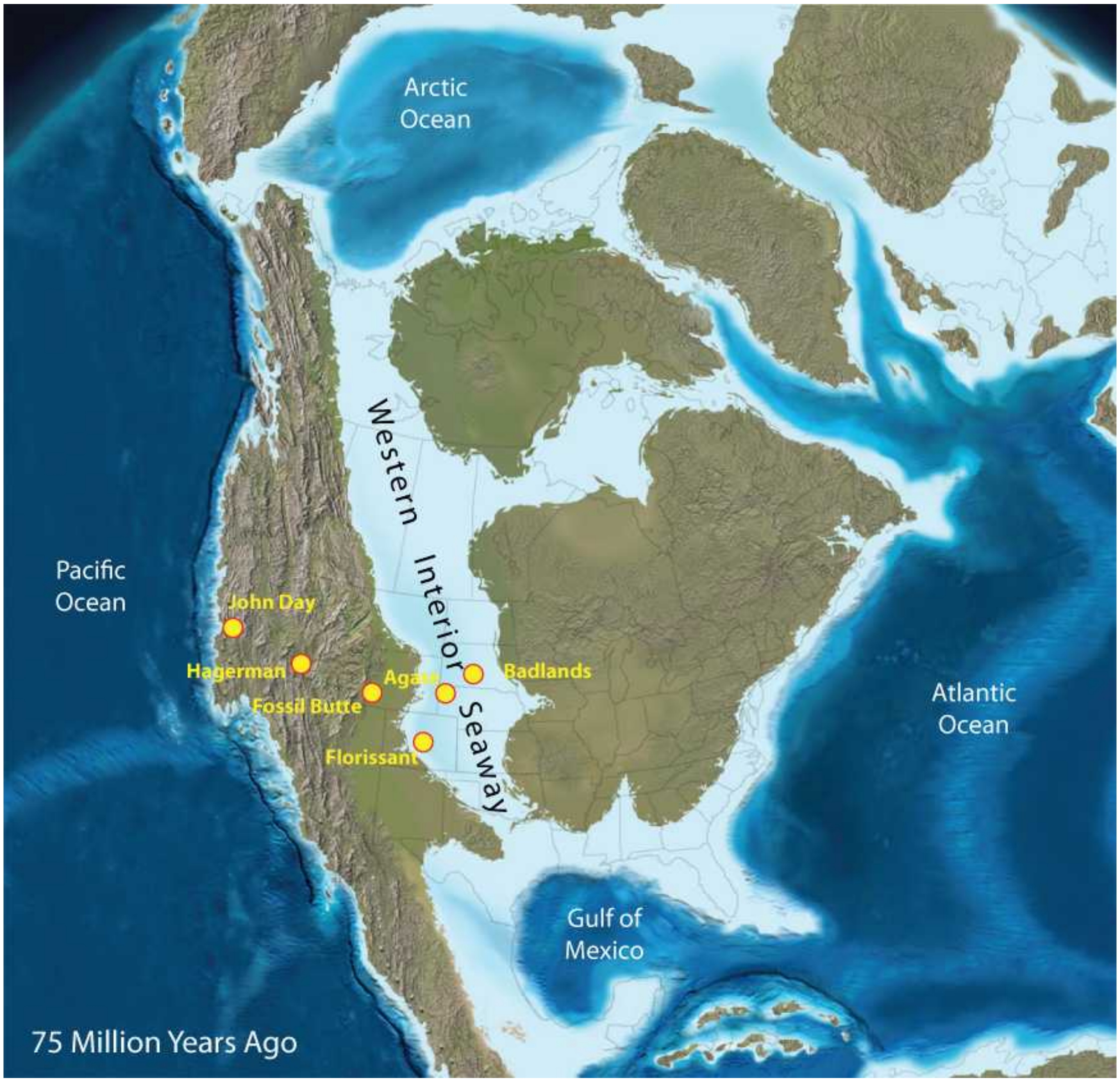


Figure 4.2. The Western Interior Seaway bisected North America during the Cretaceous from about 115 million years ago to about 65 million years ago. Marine fossils such as mosasaurs, ammonites, clams, and gigantic sea turtles found within Badlands NP attest to the vast inland sea that existed prior to the Cenozoic Era. Plesiosaurs such as the one found near Mitchell, Oregon and on display at the Oregon PaleoLands Institute near John Day Fossil Beds NM show that much of what is now Washington, Oregon, and California were part of the Pacific Ocean. (Paleogeographic map modified from and used with permission of Ronald Blakey, Northern Arizona University Department of Geology.)

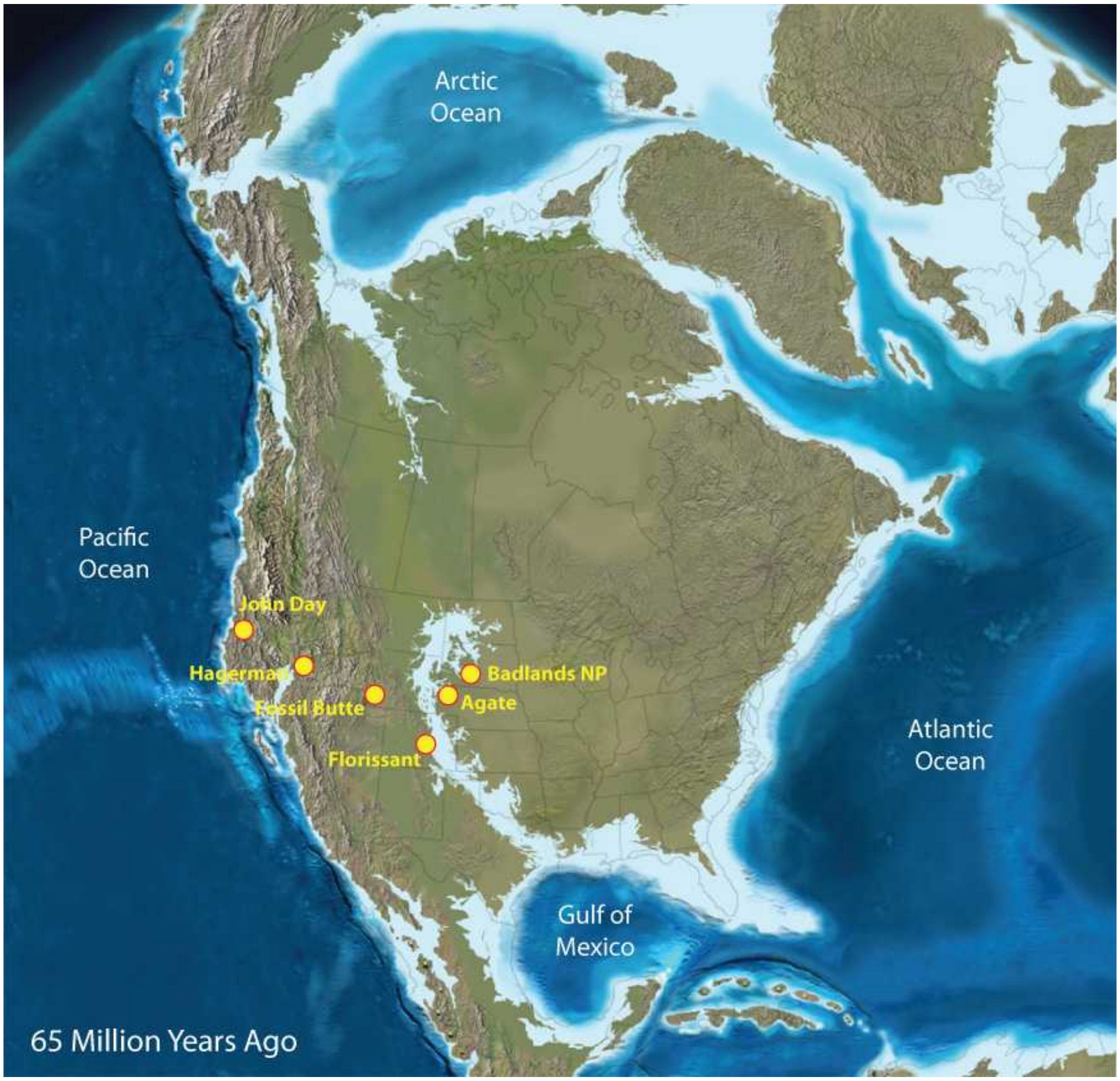


Figure 4.3. The Western Interior Seaway had greatly reduced in size by the start of the Cenozoic Era as mountains continued to rise on the west and sea levels dropped globally. (Paleogeographic map modified from and used with permission of Ronald Blakey, Northern Arizona University Department of Geology.)

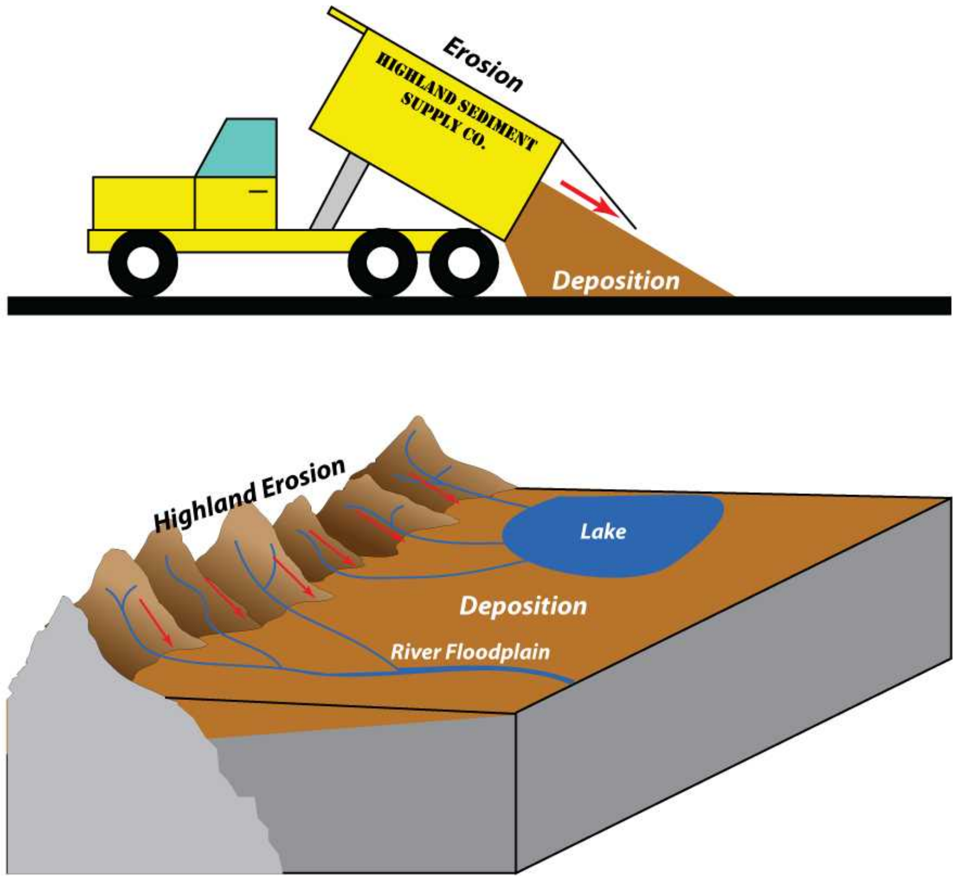


Figure 4.4. Like a dump truck deposits material as it rises, material is eroded from areas of high topography, transported (red arrows), and then deposited in areas of lower topography (depositional environments).

Digging Deeper Box 4.2. Fine sediments make fine fossils!

The type of sedimentary rock can influence how well fossils are preserved. Some of the most completely preserved fossils are found in lake deposits at Fossil Butte, Florissant Fossil Beds, and John Day Fossil Beds (Figure 3.13). Slow moving water in lakes not only helps by not moving the remains around, but by also providing fine-grained sediment which helps capture details. To help illustrate this concept, ask visitors about high definition TV or their new digital camera. The crisp resolution of HD and that new 10 megapixel camera brings new details to light. Likewise depositional environments with very small clast sizes allow lake sediments to capture minute fossil details; forming exceptional portraits of the past.

***Digging Deeper Box 4.3*. Sedimentary rocks reduce, reuse, and recycle other rocks**

The popular phrase "reduce, reuse, and recycle" is a slogan for responsible living. It also summarizes the formation of sedimentary rocks. Clastic sedimentary rocks are composed of small bits of rock, called clasts. They are mechanically weathered and eroded from other sedimentary, volcanic, or metamorphic rocks ("reduce"). They are then transported, by water or wind, and deposited elsewhere. Buried by subsequent deposits, they are compressed and can be cemented together to form new sedimentary rocks ("reuse"). When the rocks are exposed again, they are weathered and the process starts again ("recycle").

Clast Size		Depositional Environment	Rock Name	Example
smaller than 1/256 mm (0.00015in.)	Smaller	Lower Energy	Claystone	Chadron Fm (Badlands)
1/256–1/16 mm (0.00015–0.0025 in.)			Siltstone	Florissant Fm (Florissant)
1/16–2 mm (0.0025–0.08 in.)			Sandstone	Harrison Fm (Agate)
larger than 2 mm (0.08 in.)	Larger	Higher Energy	Conglomerate (rounded clasts) *or* Breccia (angular clasts)	Wasatch Fm gravel (Fossil Butte)

Figure 4.5. The names of sedimentary rocks refer to the size of the original clasts and provide clues for the type of depositional environment. Clast illustrations are shown to scale. For reference, the diameter of a human hair is about 0.002 to 0.01 in (0.05 mm to 0.18 mm), much larger than clay or silt! Claystones and siltstones can also be called "mudstone," or if they break into thin layers, "shale." Fm = formation.

Figure 4.6. Extraordinary amounts of sediment buried entire ecosystems. Fossils and distinctive blue-green rocks of the Turtle Cove Member are found in the Blue Basin of John Day Fossil Beds NM. An area of deposition 29 million years ago, today streams colored green by their sedimentary cargo carry the claystone away, recycling these rocks piece by piece and uncovering buried fossils (Box 4.3). (Photos by Jason Kenworthy.)

Digging Deeper Box 4.4. Subduction zones build mountains, fuel volcanoes, and expand the continent

A subduction zone forms where a plate capped by thin oceanic crust collides with a plate having thick, more-buoyant continental crust. Microcontinents, island chains, and seamounts are scraped off the oceanic crust and added (accreted) onto the continental crust (Figure 4.7). At a depth of about 50 miles (80 km), the diving (subducting) plate begins to "sweat" water—it is hot down there, about 2,900°F or 1,600 °C! As fluids are driven off, they rise through the crust, causing some of the overriding plate to melt, forming molten rock called **magma**. The buoyant magma continues to rise toward the surface. Magma reaching the surface erupts as **lava** from a **volcano**. As the subduction angle changes, the line of volcanoes (volcanic arc) can shift east or west. As an example of this, the modern Cascades are east of the ancestral Cascades, but far to the west of ancient Cascade ranges such as the Clarno Volcanoes. If the angle of subduction is too shallow the subducting plate does not reach hot enough temperatures to drive off water, so there are no volcanoes near the coast.

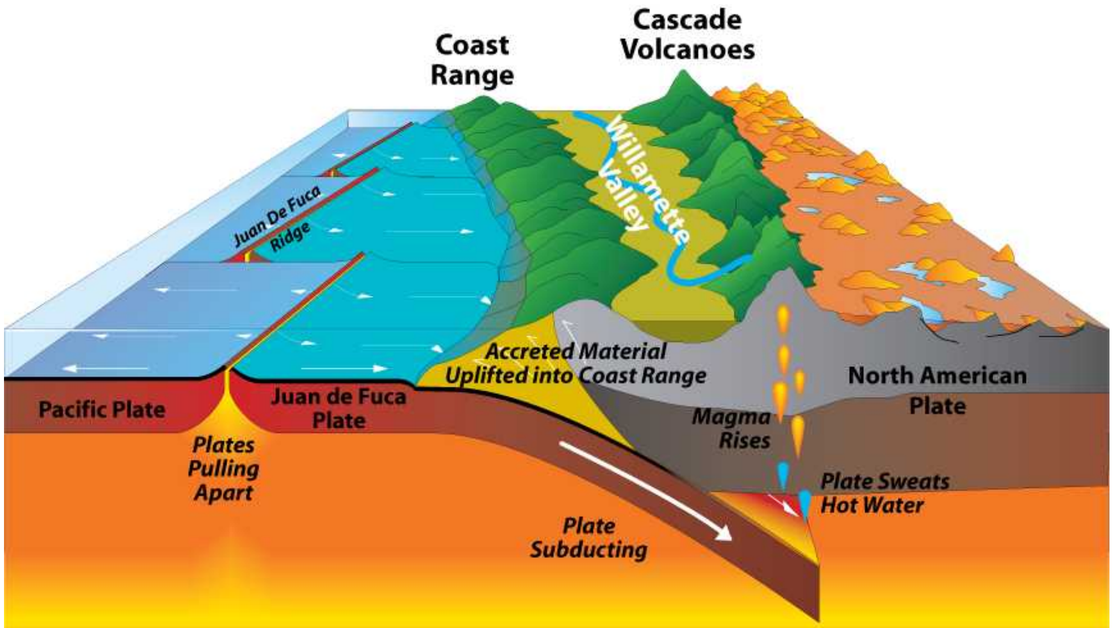


Figure 4.7. Today's Cascadia Subduction Zone is the modern expression of a subduction zone that has operated along the Pacific Northwest coast for more than 100 million years (Box 4.4). Deep angle subduction, like that pictured here and in Figure 4.9, fuels volcanoes inland from the coast. Shallower angles of subduction (Figure 4.11) may have contributed to compression and uplift of the Rocky Mountains far from the coast. (Modified from Lillie [2005].)

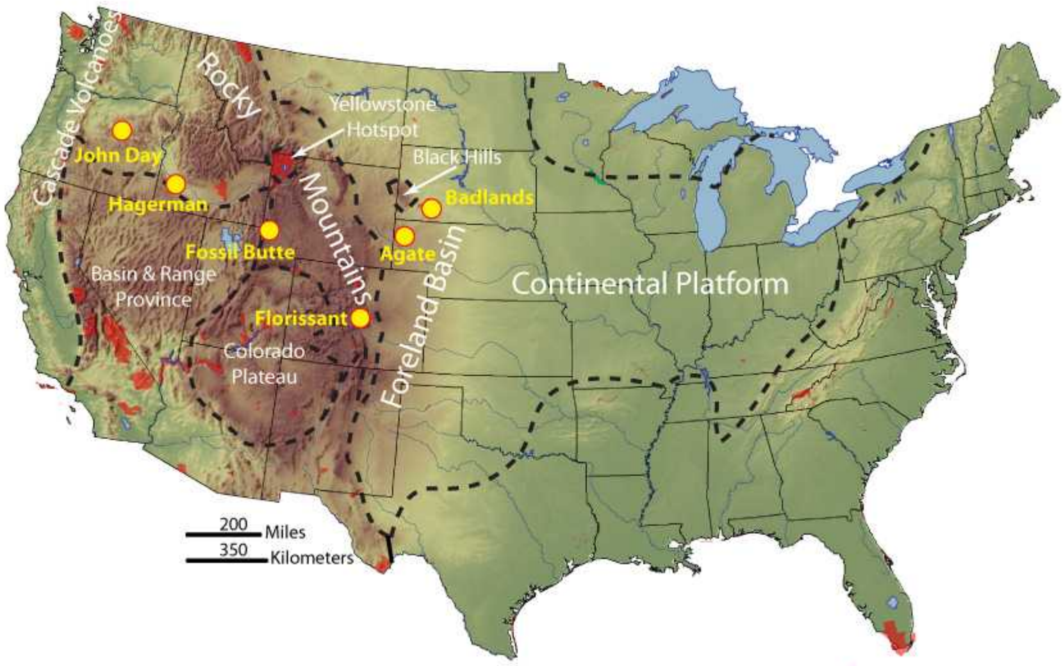
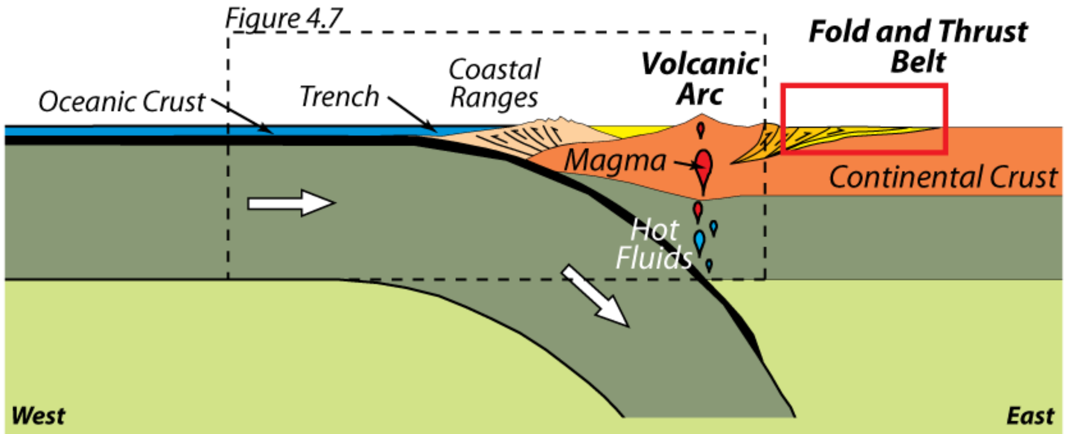


Figure 4.8. Location of Cenozoic fossil parks with respect to tectonic areas discussed in the text. (Base map modified from Lillie [2005].)



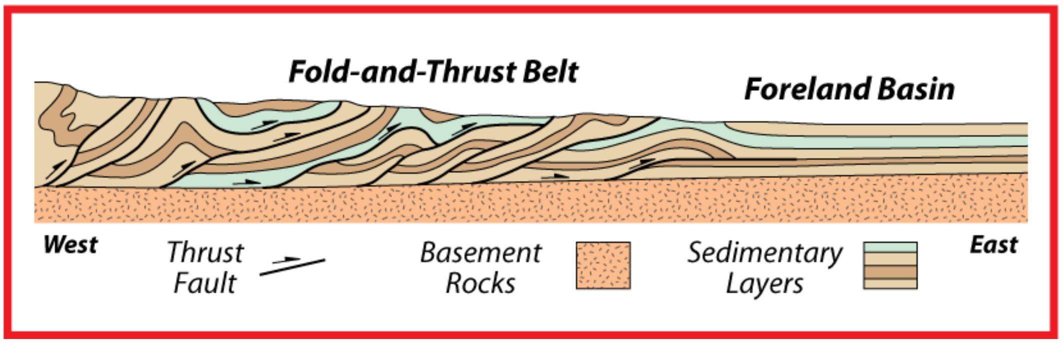


Figure 4.9. During times of steep subduction, inland fold and thrust belts develop. Sedimentary rocks are bend and shoved over each other, leaving the underlying, older igneous and metamorphic (basement) rocks undeformed. This style of Rocky Mountain building took place from about 140 to 50 million years ago. Fossil Butte NM is located along the eastern edge of a fold and thrust belt in southwest Wyoming (Figure 4.10). (Modified from Lillie [2005] and Marshak and Prothero [2001].)

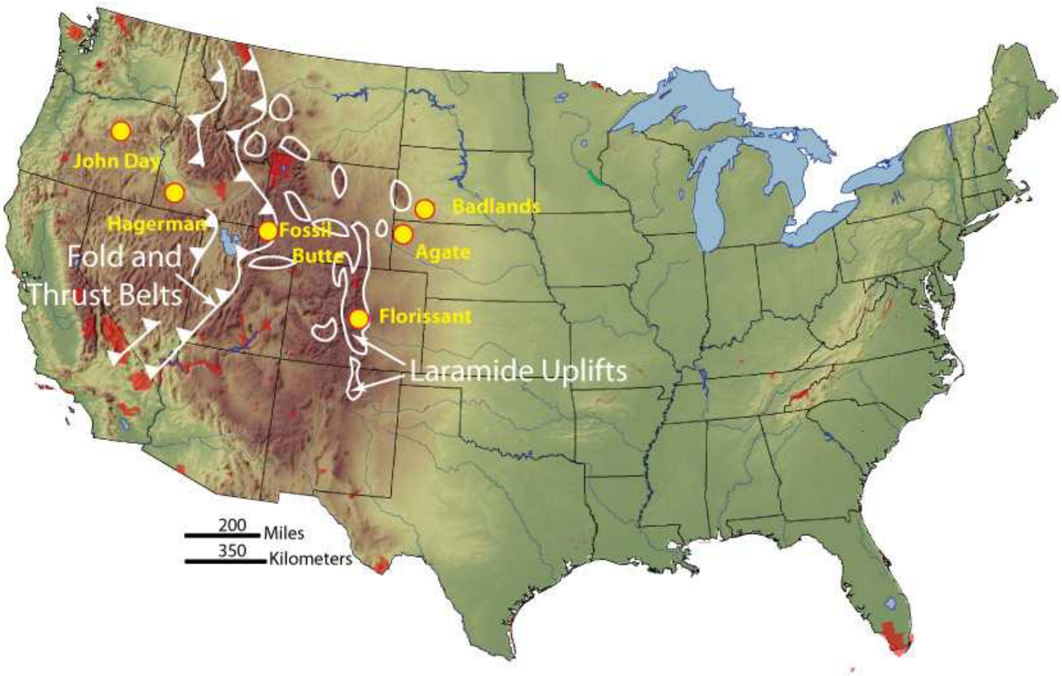


Figure 4.10. The Rocky Mountains were constructed by two primary mechanisms during the late Mesozoic and Cenozoic eras: fold and thrust belts (Figure 4.9) and Laramide uplifts (Figure 4.11). Note how far inland the fold and thrust belts and Laramide uplifts are from the coast and the subduction zone that fuels that deformation. (Base map modified from Lillie [2005].)

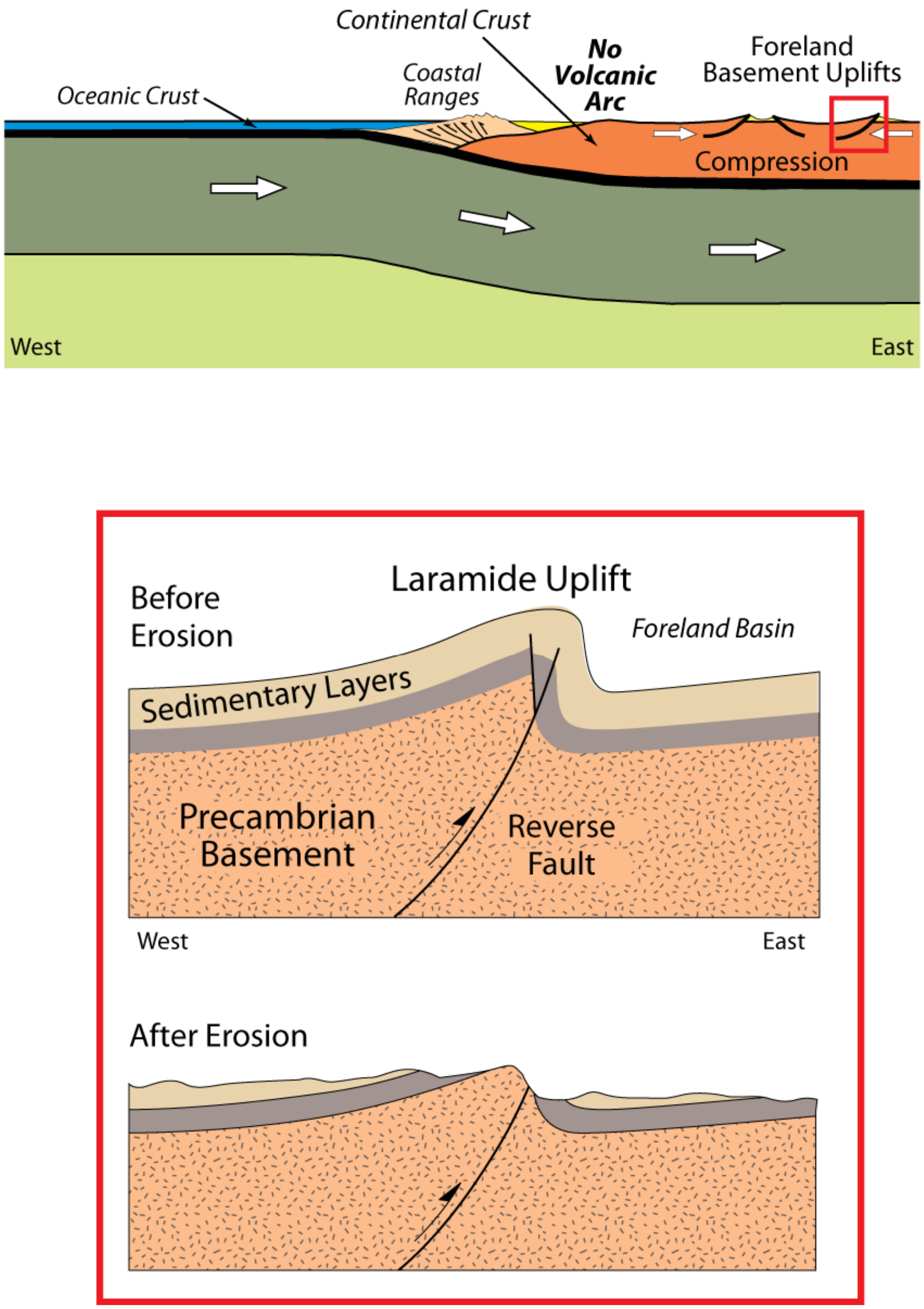


Figure 4.11. Rocky Mountain building far from the coast is thought to result from a shallow subduction angle. The shallowly-subducting plate forces older igneous and metamorphic (basement) rocks to compress and uplift along steep faults. Overlying sedimentary layers are erode, exposing the ancient basement rocks. Pikes Peak, the Black Hills and Hartville Uplift west of Florissant Fossil Beds NM, Badlands NP, and Agate Fossil Beds NM, respectively, are Laramie uplifts (Figure 4.10). This style of Rocky Mountain building occurred from about 80 to 40 million years ago. (Modified from Lillie [2005] and Marshak and Prothero [2001].)

<u>Digging Deeper Box 4.5</u>. Volcanoes are MVPs of the Cenozoic fossil parks.

In sports, MVPs are the Most Valuable Players. Without their efforts, the Big Game likely would have turned out differently. For the Cenozoic fossil parks, volcanoes are MVPs—Most Valuable for Preservation. Without them, much of our understanding of paleoecosystems would be lost.

Frequent volcanic eruptions from many sources produced immense amounts of volcanic ash. Much of this ash was transported by streams, mixed with other clasts, and redeposited as **volcaniclastic** sediment. Large volumes of sediment are critical for rapid burial of plants and animals on the road to fossilization. Ash-rich river and lake sediment is found within all the fossil parks in varying amounts, and it makes up more than 80% of the Brule Formation in Badlands NP (Larson and Evanoff, 1998)! Other exceptionally ash-rich deposits include the John Day and Mascall strata of John Day Fossil Beds NM (Fisher and Rensberger, 1972) and the Arikaree Group of Agate Fossil Beds NM (Hunt, 1990). Petrification processes (Chapter 3) require dissolved minerals to be redeposited in pore spaces, or replace original organic material. Volcanic ash is rich in silica, a prime ingredient for the petrified bones of Agate Fossil Beds NM and Badlands NP (R. Benton, pers. comm., January 2009). Silica-rich volcanic mudflows (lahars) preserved the petrified wood and nuts of John Day Fossil Beds NM (Clarno) (Manchester, 1994) and the stumps of Florissant Fossil Beds NM (Mustoe, 2008). Lava flows and lahars dammed streams, forming lakes that entombed the Bridge Creek fossil assemblage and the Florissant Formation. More indirectly at Florissant Fossil Beds NM, silica from volcanic ash fueled the diatom mats (diatoms have silica-rich exoskeletons) thought to play an important role in the preservation of the plant and insect fossils of Lake Florissant (Harding and Chant, 2000; O'Brien and others, 2008; O'Brien and others, 2002). Finally, dozens of discrete layers of volcanic ash provided a way to accurately determine when the paleoecosystems existed through radiometric dating, giving page numbers to the archived stories preserved in the Cenozoic fossil parks (Chapter 3). Volcanoes are found in many NPS areas (Decker and Decker, 2007). How many have you visited?

<u>Digging Deeper Box 4.6</u>. Rocky Mountain High?

Recent work suggests that Fossil Butte NM and Florissant Fossil Beds NM may have already been at high elevations for most of the Cenozoic Era. Investigations of fossil plant assemblages in the middle of the 20th century, such as MacGinitie (1953), suggested that the Rocky Mountains were at a relatively low elevation (a few thousand feet) and only much later were pushed to their current heights. However, during the past 20 years, studies utilizing the fossil plants of Florissant Fossil Beds NM suggest elevations of 6,200 ft (1,900 m) to 14,800 ft (4,500 m), compared to today's 8,400 ft (2,560 m) (Meyer, 2001, 2003). Meyer (2001) prefers an interpretation of paleoelevations similar to or slightly higher than today's. These paleoelevation estimates are derived from a variety of methods comparing Florissant's estimated paleotemperature to those of other assemblages of fossil plants from different latitudes and elevations closer to sea level. Estimates of the rate of decrease in temperature for a given increase in elevation or latitude are then applied to determine a paleoelevation for the Florissant paleoecosystem.

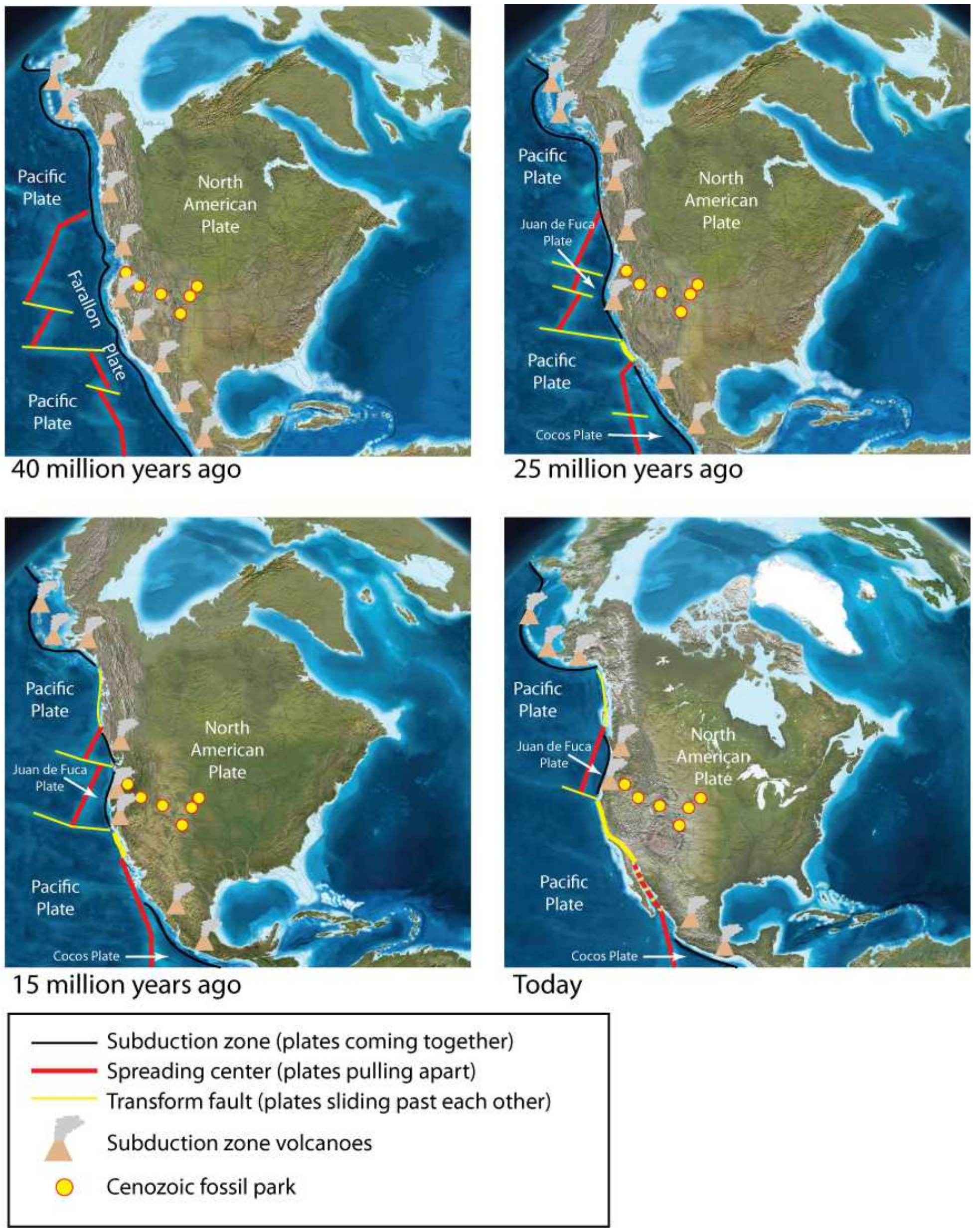


Figure 4.12. By the beginning of the Cenozoic Era, most of the Farallon Plate had subducted beneath North America. The Juan de Fuca and Cocos plates are remnants of the much larger Farallon Plate. Subduction of the Farallon Plate fueled volcanoes along the west coast beginning during the Mesozoic Era. During the Cenozoic Era, subduction zone volcanoes blanketed John Day Fossil Beds NM (westernmost dot) with volcanic materials. The San Andreas Fault—of California earthquake fame—developed (thick yellow line) when the Pacific Plate began to slide north-northwest past the North American plate about 25 million years ago. Because there is no longer a subducting plate, there are no active volcanoes along the San Andreas Fault. The Juan de Fuca and Cocos plates now fuel volcanoes in the Pacific Northwest and Central America. (Paleogeographic maps modified from and used with permission of Ronald Blakey, Northern Arizona University Department of Geology.)

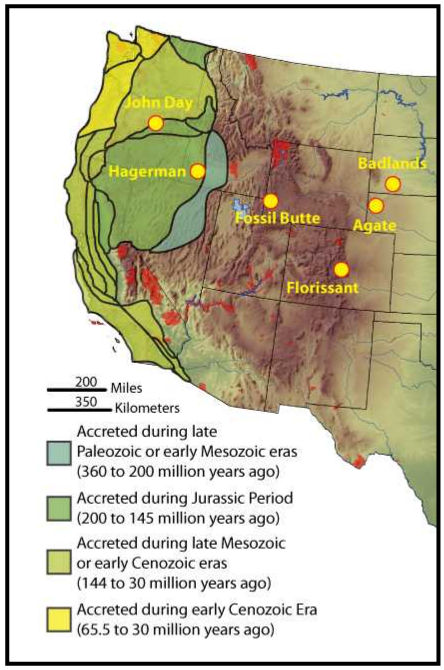


Figure 4.13. Westward expansion of North America has been occurring for more than 150 million years (Figure 4.14)! Rocks making up much of Washington, Oregon, Idaho, Nevada, and California were manufactured somewhere else, transported in from the Pacific, and added (accreted) onto the western edge of the continent. This map shows the major terranes that built North America westward and the approximate time each came crashing in. John Day Fossil Beds NM contains rocks and fossils that provide evidence that the Pacific coastline was nearby during the beginning epochs of the Cenozoic Era. (Base map modified from Lillie [2005], after Coney and others [1980].)

Figure 4.14. Like groceries coming together at the end of a check-out stand conveyor, terranes were "accreted," added onto, the west coast of the continent. As ocean crust subducted, microcontinents, volcanic islands, and undersea volcanoes (collectively comprising terranes) grew the continent westward. Undersea volcanoes and volcanic islands, were the last pieces to be accreted. They were just off the coast 50 million years ago and now form much of Oregon's Coast Range. (Grocery store photos by Robert J. Lillie; paleogeographic maps modified from and used with permission of Ronald Blakey, Northern Arizona University Department of Geology).

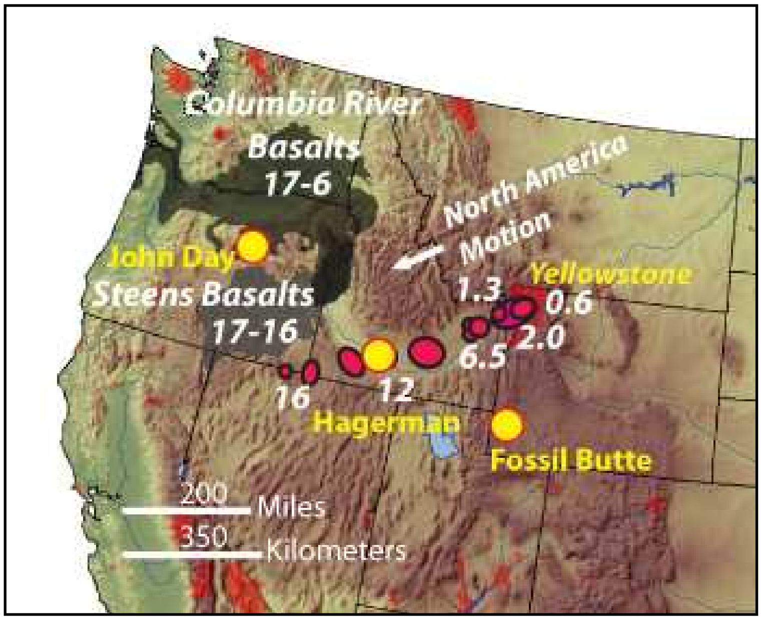


Figure 4.15.The Columbia River Basalts (visible in John Day Fossil Beds NM) and Steens Basalts erupted over an enormous area of the Pacific Northwest beginning about 17 million years ago (numbers on the map represent major volcanic eruptive episodes, in millions of years before present). The surfacing of the Yellowstone Hotspot around the same time might have fueled these eruptions. As North America moves to the southwest over the stationary hotspot, eruptions tracked across Idaho's Snake River Plain. Today Yellowstone National Park overlies the hotspot. The 3.2 million-year-old paleoecosystems of Hagerman Fossil Beds NM developed alongside a lake that filled a depression after the region passed over the hotspot millions of years earlier. (Base map modified from Lillie [2005].)

Chapter 5

Greenhouse to Icehouse: Tropical forests are replaced by woodlands, savannahs, and grasslands as global climate cools and dries.

Earth's **climate** has changed throughout its history. These changes are recorded in the fossil record of paleoecosystems. Over long time scales (tens- to- hundreds of millions of years), conditions on Earth can be broadly characterized as "greenhouse" or "icehouse" climates. During greenhouse times, there is very little, if any, permanent ice on either pole (Figure 5.1). Warm temperate climates are found at high latitudes. During icehouse conditions, global climate is cool enough to support large ice sheets at one or both poles. Tropical or near-tropical conditions are confined to a much narrower band around the equator and temperate zones span more of the globe with cool temperate conditions at high latitudes, and warm temperate climate at mid latitudes (Figure 5.1). Today, we live on an icehouse Earth, one that is actually quite cold. Does this mean we don't have to worry about human-caused climate change (global warming)? We certainly *should* be concerned! Chapter 7 examines human-caused climate change in the context of long-term climate change during the Cenozoic (this chapter). Today we live on a cold, icehouse Earth, following an "ice age."

Climate has oscillated between the two conditions a number of times throughout Earth history (Figure 5.2) (Frakes and others, 1992). The most recent transition from a greenhouse to an icehouse Earth occurred during the Cenozoic Era and is recorded in the paleoecosystems of the Cenozoic fossil parks (Figure 5.3). The most recent transition from a greenhouse to an icehouse world was not a slow, steady one, but full of bumps and wiggles, with an overall trend toward a cooler and drier planet. By about two million years ago, after the youngest ecosystem represented in the Cenozoic fossil parks existed (Hagerman Fossil Beds NM), the planet's climate was so cold that ice sheets advanced and retreated a number of times during the aptly named "ice ages" (Chapter 7).

Chapter 1 provided an introduction to the varied paleoecosystems of the Cenozoic fossil parks. In this section they are grouped into greenhouse and icehouse paleoecosystems and described chronologically though time. As suggested in Box 3.6, an interpretive approach to remember is that the Cenozoic fossil parks connect the greenhouse world of tropical forests, dinosaurs, and early mammals to the icehouse world of grasslands, modern horses, wooly mammoths, and saber-toothed cats. Each park tells a chapter of the story of that transition. The greenhouse parks range in age from 52 to 34 million years old and thus are all from the Eocene Epoch (Figure 1.2). Fossil Butte NM, John Day Fossil Beds NM (Clarno and lower John Day Formation paleoecosystems), Badlands NP (Chadron Formation), and Florissant Fossil Beds NM preserve greenhouse paleoecosystems. Icehouse paleoecosystems are found after the Eocene–Oligocene transition 34 million years ago in four parks: Badlands NP (Brule and Sharps formations), John Day Fossil Beds NM ("upper" John Day Formation, Mascall and Rattlesnake Formations), Agate Fossil Beds NM, and Hagerman Fossil Beds NM. The last section of this chapter describes some of the factors that influenced Cenozoic climate change.

How do paleontologists reconstruct ancient climates? Just like detectives work with evidence found at a crime scene to reconstruct what happened, paleontologists look for fossil clues to interpret temperature, precipitation, and landscape patterns that affected ancient ecosystems. There are many methods, but three major sources of information will be utilized in this manual: tiny microfossils called **Foraminifera**, fossil plants, and ancient soil layers called **paleosols** (Boxes 5.1, 5.2, and 5.3; Figures 5.4, 5.5, 5.6, and 5.7). As an interpreter, it is easy to be overwhelmed by the differing observations and scientific interpretations present in the ever-expanding literature on Cenozoic climate change. What is important to recognize is that, just like age-dating is effective when a variety of relative and absolute methods suggest the same age, ancient climate information from a variety of sources presents a more robust picture. Paleontologists must ask questions such as: “Are the climatic conditions suggested by leaf fossils consistent with the depositional environment inferred from the type of rocks or precipitation amounts estimated from the paleosols?” The Cenozoic fossil parks are particularly good places to study paleoclimates because of the high diversity of plants, animals and paleosols that are preserved *together* in communities.

Paleocene Epoch: From 65.5 to 56 million years ago, greenhouse climates continued after the dinosaurs’ extinction, before the stories of the Cenozoic fossil parks.

The very first chapter of life after the dinosaurs—the Paleocene Epoch—is not recorded in the Cenozoic fossil parks. As described by Prothero (2006), this time from 65.5 to 55.8 million years ago was a “recovery” period following the major extinction at the end of the Mesozoic Era. Mammals became the dominant large vertebrates filling many of the niches vacated by the dinosaurs (Chapter 6). The climate of the Paleocene continued the greenhouse conditions similar to those the last dinosaurs experienced. This included warming toward the hottest Cenozoic climate, during the Eocene between 52 and 50 million years ago. As shown on Figure 5.3, deep-sea temperatures cooled slightly during the early Paleocene, but began a pronounced warming trend about 59 million years ago. The wet and warm climate of the Paleocene supported swampy, nearly-tropical forests as far north as what is now northeastern Wyoming, southern Montana, and North Dakota. Visitors can see evidence of these forests being transported by coal trains throughout the West. The vast coal fields of northeastern Wyoming’s Powder River Basin are remains of these Paleocene forest paleoecosystems. Although the Cenozoic fossil parks do not preserve Paleocene paleoecosystems, other western NPS areas do preserve Paleocene fossils, including Theodore Roosevelt NP (North Dakota); Grand Teton NP (Wyoming); Santa Monica Mountains National Recreation Area (California); Bryce Canyon NP (Utah); Capitol Reef NP (Utah); Cedar Breaks NP (Utah); and Big Bend NP (Texas).

Eocene Epoch: The 52 to 34 million-year-old nearly-tropical lakes and forests of the "greenhouse" fossil parks—Fossil Butte NM, John Day Fossil Beds NM, Badlands NP, and Florissant Fossil Beds NM—exemplify the warmest time of the Cenozoic.

From the bottom of the sea (Zachos and others, 2008; Zachos and others, 2001) to the forests of western North America (Wing and Greenwood, 1993; Wolfe, 1994), the Eocene, particularly the early Eocene, was the warmest time period of the past 65 million years—a true greenhouse with small or no permanent ice sheets at either pole (Figure 5.1). In fact, petrified trees from a 50 million-year-old temperate forest have been discovered in the far north of Arctic Canada (Francis, 1988). Nearly-tropical or warm temperate lakes and forests comprised the paleoecosystems of this greenhouse world at Fossil Butte NM, John Day Fossil Beds NM, Badlands NP, and Florissant Fossil Beds NM (Figure 5.8).

Global climate, already warming 59 million years ago, rapidly spiked 55 million years ago at the beginning of the Eocene (Figure 5.3). This rapid warming occurred over about 200,000 years and is further described in the last section of this chapter. Cenozoic climate warmed to a peak known as the Early Eocene Climatic Optimum, 52 million years ago (Zachos and others, 2008). Like a roller coaster dropping off the highest hill, climate then began its long-term cooling—with a few smaller ups and downs to keep things interesting. A brief warming occurred from about 44 to 39 million years ago, termed the Mid-Eocene Climatic Optimum (Zachos and others, 2008). Climate continued to cool until the end of the Eocene 34 million years ago. Prothero (2006) repeats Miller's (1992) choice of words referring to the last three million years of the Eocene (37 to 34 million years ago) as the "doubthouse" as global climate was cooling to near icehouse conditions.

<u>Fossil Butte National Monument</u>

The paleoecosystems of Fossil Butte NM existed during the warmest time period of the past 65.5 million years (Figure 5.3). Fish, stingrays, crocodiles, alligators, and turtles lived in Fossil Lake. At the same time, palm trees, elms, hickories and walnuts, and sumacs forested the surrounding areas (Figures 1.4 and 5.8) (Buchheim, 1998; Grande, 1984, 1994, 2001; Manchester and Kester, 2002; P. Kester, pers. comm., October 2009). Interpreters can connect this ecosystem to similar ecosystems in Florida's Everglades NP, which is the only place on Earth today where crocodiles and alligators coexist. However, instead of being on the coast at sea level, Fossil Lake was more than 500 miles (800 km) from the coast, and likely amidst mountains rising 1,500 ft (475 m) or more above the basins (Fricke, 2003).

<u>John Day Fossil Beds National Monument (Clarno Formation and lower John Day Formation paleoecosystems)</u>

Eight million years younger than the paleoecosystems of Fossil Butte NM, and only about 60 miles (100 km) from the coast, the Clarno Nut Beds ecosystems of John Day Fossil Beds NM existed along the flanks of the then-active Clarno Volcanoes (Figures 1.5 and 5.8). Plants that today would seem more at home in the tropics of Asia, Central and South America, or Africa were abundant in the nearly-tropical forest: palms, avocado, walnuts, sycamores, cycads, grapes, and even bananas (Manchester, 1981; Manchester, 1993; Manchester, 1994; Manchester, 1995; Wheeler and Manchester, 2002). Based on leaf shape and comparison with modern representatives of the same families, Manchester (1994) suggests a mean annual temperature between 68° and 77°F (20° and 25°C) with coldest month temperatures of about 50°F (10°C) (Figure 5.5). Clarno Nut Beds paleosols are similar to soils found today in the Transmexican Volcanic Belt of central and southern Mexico and suggest a similarly warm climate (>73°F, or 23°C mean annual temperature) with abundant rainfall as high as 100 inches (250 cm) at the lower elevations (Retallack and others, 2000). The 40 million-year-old paleosols of the Hancock Mammal Quarry are like those of open deciduous tropical forests near Oaxaca, Mexico with mean annual temperatures greater than 73°F (23°C) and rainfall amounts on the order of 22–39 inches (55–100 cm). As an indicator of cooler climates to come, the last (youngest) crocodile fossil in Oregon was discovered in the Hancock Mammal Quarry (Hanson, 1996; Retallack and others, 2000). Like today, crocodiles were probably intolerant of cold climates. Younger still are the blood-red paleosols of the Big Basin Member of the John Day Formation. They are visible looking to the far left of the Thomas Condon Paleontology Center’s porch, and accessible along the Painted Cove Trail (Painted Hills unit). These layers are the last of the thick, red, deeply-weathered paleosols in John Day Fossil Beds NM (Retallack and others, 2000). By 38 million years ago soils in the Painted Hills area were similar to those found today in the humid and warm Central American Range of Costa Rica, Nicaragua, and Honduras—areas that receive between 60 and 120 inches (150 and 300 cm) of precipitation, have a mean annual temperature of at least 73°F (23°C), and experience a dry season of only about three months (Retallack and others, 2000).

Badlands National Park (Chadron Formation paleoecosystems)

By 37 million years ago, global climate was continuing to cool but still able to support forested ecosystems well north of the equator and well inland. Prothero (2006) uses Miller’s (1992) term “doubthouse” world for this time period. Paleosols of the 37 to 34 million-year-old Chadron Formation in Badlands NP are indicative of warm, humid, subtropical forests (Figures 1.14 and 5.8) (Retallack, 1983). Although rare, alligator fossils imply an ecosystem without freezing temperatures (Macdonald, 1982). Based on the paleosols, Retallack (1983) suggests that the Chadron Formation paleoecosystems transitioned from humid and subtropical to less humid and warm temperate from about 37 to 34 million years ago. The woodlands became increasingly open during this time as dry seasons became longer.

Florissant Fossil Beds National Monument

The lahar and lake fossils of Florissant Fossil Beds NM are 34 million years old, placing them at the very end of the Eocene (Figures 1.19 and 5.8) (Evanoff and others, 2001). The towering *Sequoia*-like trees—more than three times as tall as the ponderosa pines visible there today—also have wider growth rings than today's California redwoods, suggesting a more favorable climate (Gregory-Wodzicki, 2001). Plants from the palm family suggest a subtropical ecosystem, while the two most common fossil leaves at Florissant, *Fagopsis* (beech family) and *Cedrelospermum* (elm family) are today distributed in eastern North America. Today's descendents of the Florissant tsetse fly are only found in equatorial Africa. Paleontologists have compared the Florissant paleoecosystem to forests in Florida, Mexico, Argentina, southern Texas, southeast Asia, the Pacific coast of North America, the southern Rocky Mountains, and the southern Appalachians (Boyle and others, 2008; Meyer, 2003). Mean annual temperature was somewhere between 52° and 64°F (11° to 18°C); Meyer (2003) suggests about 55°F (13°C). Paleoelevation estimates also vary widely, from about 6,200 ft (1,900 m) to about 13,560 ft (4,130 m) (Meyer, 2001). Florissant was likely at an elevation at least as high as today (8,400 ft or 2,560 m; Box 4.6). Such differences illustrate the difficulty of accurately comparing paleoecosystems to modern ecosystems. These were some of the last greenhouse paleoecosystems of the Cenozoic fossil parks—the icehouse world was on the horizon.

Oligocene Epoch: Woodlands, savannahs, and grasslands—34 to 23 million years old—of John Day Fossil Beds NM and Badlands NP replaced nearly-tropical forests, signaling the beginnings of an icehouse Earth.

During the early Oligocene, global climate cooled significantly and very quickly, ushering in icehouse global climatic conditions (Figure 5.3). Deep ocean water cooled and the Antarctic ice sheet greatly expanded over a period of about 300,000 years (Zachos and others, 2001). High latitude sea surface temperature cooled by about 9°F (5°C) from about 34 to 33 million years ago (Liu and others, 2009). This change was not confined to the oceans. Based on leaf fossils, Wolfe (1994) suggests that in North America, mean annual temperatures may have dropped as much as 14–22°F (8–12°C) in about a million years. Ice sheets surrounding the South Pole may have been present for a few million years but large, permanent ice sheets were in place by 33 million years ago. The nearly-tropical forests and lakes present during the Eocene disappeared from the Cenozoic fossil parks. In their place were more open woodlands, savannahs, and early grasslands (Figure 5.9). Global climate warmed during the late Oligocene and experienced periods of increased global aridity. The first evidence in the Cenozoic fossil parks for these icehouse conditions are archived in some of the most colorful rocks in the parks. Badlands NP's Brule and Sharps formations make up much of the striped "Wall" in the park. The artistically-named Painted Hills and Blue Basin preserve paleoecosystems of the Big Basin and Turtle

Cove members of the John Day Formation within John Day Fossil Beds NM. The pink rocks of the Kimberly Member of the John Day Formation are found near the top of Sheep Rock.

Badlands National Park (Brule Formation and Sharps Formation paleoecosystems)

The steep, jagged, and eroded sediments of the Brule Formation form most of “the Wall” in Badlands NP and span just over three million years from about 33.4 to 30 million years ago (Figures 1.14 and 1.15) (Prothero and Emry, 2004). In great contrast to the Chadron Formation’s warm humid subtropical ecosystems, tan and gray paleosols of the lower Brule Formation (known as the Scenic Member) suggest savannah woodlands with scattered trees, small shrubs, and bunch grasses or gallery woodlands along streams (Figure 5.9) (Retallack, 1983). Some of the dramatic red stripes characteristic of the Scenic Member are paleosols indicative of open areas next to streams, perhaps populated by early grasses (Figure 5.7). As another indicator of drying climate, watering holes developed, similar to those on the African savannah today. These watering holes attracting herbivores such as the rhino *Subhyracodon* as well as omnivorous scavengers such as *Archaeotherium* (the “Big Pig”, for which the Big Pig Dig excavation was named). The upper layers of the Brule Formation, called the Poleslide Member, indicate increased drying. There are higher amounts of eolian sediment, suggesting a high supply of sediment and only sparse vegetation to hold it in place. Such wind-blown deposits are nonexistent in the mostly-forested paleoecosystems of the earlier (greenhouse) Cenozoic fossil parks. Alligators are completely gone by the time of the Poleslide Member, indicating a temperate, perhaps even cool temperate climate. Tan paleosols suggest semi-arid conditions with about 16 to 20 inches (40 to 50 cm) of precipitation (Retallack, 1983). The lack of water and sparse vegetation may explain why Badlands fossils are much smaller in the Brule than in the Chadron Formation (Retallack, 1983). Visitors and interpreters hiking the popular Fossil Exhibit Trail are walking among evidence of these Brule ecosystems.

The Oligocene record at Badlands National Park continues through the Sharps Formation which forms the very highest pinnacles of “the Wall.” Although not as fossiliferous as the Brule Formation, the Sharps Formation continues the story of cooling and drying and spans from about 30 to 28 million years (Figure 1.16) (Tedford and others, 2004). Paleosols of the Sharps Formation evoke a dry, steppe-like ecosystem with semi-arid conditions. By this time, there were only 14 to 18 inches (35 to 45 cm) of precipitation per year and “mildly cool temperate” temperatures (Retallack, 1983). The lack of aquatic or amphibious mammals imply a pronounced dry season.

John Day Fossil Beds National Monument (John Day Formation paleoecosystems)

John Day Fossil Beds NM contains a fossil record that spans the entire 11 million years of the Oligocene. It begins with the colorful Painted Hills. In stark contrast to the deep red and deeply-weathered paleosols of the late Eocene, the Painted Hills exhibit dramatic hues of yellow and brown within less-weathered paleosols that have streaks of red and black (Figure 1.7). These ancient soils represent a variety of humid to subhumid—from 16 to 53 inches (40 to 135 cm) of annual precipitation—woodland paleoecosystems (Retallack and others, 2000). One of the best preserved paleoecosystems is the Bridge Creek Flora, interpreted along the Fossil Leaf Trail in the Painted Hills unit. With more than 110 species of leaves, and 58 species of plant reproductive parts, the Bridge Creek plant fossils represent a temperate deciduous forest similar to those in China or parts of North America (Meyer and Manchester, 1997). At the Painted Hills, the most common plant fossils are *Alnus* (alder), *Betula* (birch), *Quercus* (oak), and *Metasequoia* (dawn redwood). *Metasequoia*, a deciduous conifer, was particularly common, and is now the state fossil of Oregon (Figure 5.10). Meyer and Manchester (1997) estimated a mean annual temperature between 48° and 52°F (9° and 11°C), but with a wide seasonal range of temperatures subject to winter frosts (Figure 5.5). Rainfall might have been on the order of 39 to 59 inches (100 to 150 cm). Compare these 33 and 31 million-year-old paleoecosystems with those of the Brule Formation of Badlands NP (Figure 5.9). Those of John Day Fossil Beds NM are more forested, suggesting wetter conditions, not surprising given how much closer the John Day ecosystems were to the coast. The Cascade Volcanoes were likely only at moderate elevation, perhaps up to 2,600 ft (800 m), producing only a small rain shadow effect (Kohn and Fremd, 2007)

The continuous record of Oligocene life in central Oregon continues at the Sheep Rock, Blue Basin, and Foree areas of John Day Fossil Beds NM. The next major paleoecosystem is the Turtle Cove assemblage, which spans from about 30 to 26 million years ago. Taking a walk on the Island in Time Trail through the Blue Basin, visitors are surrounded by archived evidence of these paleoecosystems as well as plaster casts of some of the animals that lived there. The earlier red and brown paleosols are gone, replaced with the distinctive green and blue hues of the Sheep Rock unit. These green and blue paleosols suggest a climate continuing to cool and dry, with more “monotonous” vegetation (Figures 1.8 and 5.6) (Retallack and others, 2000). The green paleosols are similar to those found in intermountain basins south of the border in the Transmexican Volcanic Belt, with a grassy deciduous forest overtop tall bunches of grass (not yet the sod-forming kind, like in your lawn) and short trees. Retallack and others (2000) estimated 10 to 26 inches (25 to 66 cm) of precipitation, a seasonal climate with frequent winter frosts, although the very common large turtles (*Stylemys*) seem to indicate that winters were not too harsh and snowy. These are some of the most diverse and fossiliferous paleoecosystems preserved in John Day Fossil Beds NM. Compare the ecosystems of the Turtle Cove assemblage with those of the similarly-aged Sharps Formation at Badlands NP (Figure 5.9). The ecosystems at Badlands NP were much dryer, approaching savannahs and steppes, a preview of things to come to Oregon during the Miocene.

The approximately 25.8 to 24.4 million-year-old Kimberly Member of the John Day Formation represents the youngest Oligocene paleoecosystem in John Day Fossil Beds NM (Albright and others, 2008; Hunt and Stepleton, 2004). Unlike the green and blue paleosols of the Turtle Cove, the Kimberly

Member is characterized by pinkish-white layers that represent increasingly dry and more open vegetation (Figures 1.9 and 5.6). This was a time of an increase in global temperature and aridity (Figure 5.3). The Kimberly paleosols formed under semi-arid sagebrush desert or scrubland paleoecosystems with about 12 to 24 inches (30 to 61 cm) of precipitation annually (Retallack, 2004).

Miocene Epoch: From 23 to 5 million years ago savannahs and grasslands, like those preserved at John Day Fossil Beds NM and Agate Fossil Beds NM, spread around the world during the Miocene.

Following a pulse of glaciations to start the Miocene, climate warmed globally, reaching a peak between about 16 and 14 million years ago when the Antarctic ice cap was vastly reduced in size (Figure 5.3) (Zachos and others, 2008; Zachos and others, 2001). In western North America this increase in temperature occurred without a pronounced increase in precipitation, leading to the spread of savannahs and grasslands—a worldwide phenomenon during the Miocene (Figure 5.11). Suggestive of sparse vegetation, wind-blown deposits were common in the continental interior, much as they were in the Oligocene of Badlands NP. During times of global aridity, such about 19.2 million years ago, watering holes (think of today's Serengeti Plains of Africa) were important parts of ecosystems. The bone beds of Agate Fossil Beds NM record one such watering hole. The Miocene ecosystems of John Day Fossil Beds NM span much of that epoch and illustrate the cooling and drying of local climate. By 7 million years ago, the Cascade rain shadow was reducing rainfall in the eastern parts of Oregon and true grasslands spread (see the Rattlesnake mural in Figure 5.11). John Day Fossil Beds NM also preserves evidence of the immense Columbia River Basalts that began erupting about 16 million years ago (Chapter 4).

<u>John Day Fossil Beds National Monument ("upper John Day Formation" paleoecosystems)</u>

The paleoecosystems of the upper John Day Formation at John Day Fossil Beds NM span from about 24.4 to 18.4 million years ago (Albright and others, 2008). Green and brown paleosols in the Balm Creek Member suggest a still semi-arid climate but more humid conditions and a return of wooded grassland and desert shrubland ecosystems (Retallack, 2004). Desert scrub reappears again following subsequent drying. The first (oldest) sod grass soils in Oregon appear by about 19 million years ago, similar in age to those of Agate Fossil Beds NM (Retallack, 2004). This may have also heralded the beginning of the wet winter and dry summer moisture pattern (like the Pacific Northwest today) compared to the wet summer and dry winter moisture pattern of the Oligocene (like the Great Plains today). These short sod grasslands probably were surrounded by dry woodlands.

<u>Agate Fossil Beds National Monument</u>

The oldest rocks in Agate Fossil Beds NM are exposed along the *Daemonelix* Trail and are referred to the Harrison Formation. These thick, gray sediments are wind-blown and rich with volcanic ash. They are at least 22.9 million years old (Izett and Obradovich, 2001). As summarized by Retallack

(2004) this was shortly after a period of global aridity near the Oligocene-Miocene boundary. Hunt (1985) compares these sediments to modern semi-arid or desert "dikaka" deposits which are wind-blown sand stabilized by scrub or grass vegetation. Today similar ecosystems are found in the Arabian peninsula (Glennie, 1970). A gap of a few million years separates the lower Harrison Formation deposits from the bone beds of the Fossil Hills at Agate Fossil Beds NM. The bone beds illustrate the importance of water to ecosystems of the semi-arid continental interior during another period of global aridity 19.2 million years ago (Retallack, 2004). These bone beds (primarily the rhinoceros *Menoceras arikarense*) are found in abandoned stream channels that served as watering holes during times of seasonal dry climate (Figures 1.20, 1.21, and 5.11) (Hunt, 1990). Several months passed before the bones were buried again when rains returned to the area (Hunt, 1990). Semi-arid or at least seasonally dry conditions continued well after the bone bed was buried. The rock layers of the Fossil Hills above the bone beds contain evidence for continued eolian deposition, with paleosols indicating grasses and low shrubs covering the area (Hunt, 1990). Trees and large woody brush were rare or just not preserved. Savannah woodlands may have existed nearer to streams. Retallack (1997) suggests these ecosystems were home to some of the first sod grasslands on the Great Plains. Some small lakes, now preserved as isolated limestone deposits, dotted the landscape (Hunt, 1990).

<u>John Day Fossil Beds National Monument (Columbia River Basalt Group paleoecosystems)</u>

Extraordinary thicknesses of Columbia River Basalts (Chapter 4) blanked much of northern Oregon and southern Washington during the middle Miocene Epoch. The Picture Gorge Basalts, now found at the very top of Sheep Rock and framing Picture Gorge, erupted between about 16.5 and 15.5 million years ago (Figure 1.11). This was during the warmest interval since the Eocene, known as the middle Miocene climatic optimum (Zachos and others, 2001) (Figure 5.3). Voluminous greenhouse gasses erupted along with the basalt may have contributed to these globally warm temperatures (Hodell and Woodruff, 1994). Although no animal fossils are found in association with the basalts at John Day Fossil Beds NM (and would not be expected to be preserved in molten lava!), a well-preserved paleosol record allows reconstruction of the ancient environments. Paleosols between basalt flows (look for the fiery red layers in Picture Gorge) suggest seasonally dry peat swamps and forests with up to 24 to 47 inches (60-120 cm) of precipitation annually and annual average temperature of between 46 and 61°F (8 and 16°C) (Sheldon, 2006). Central Oregon's climate returned, albeit briefly, to temperate, subhumid conditions that were warmer and wetter than during the Oligocene, but far from the nearly-tropical forests of the Eocene.

<u>John Day Fossil Beds National Monument (Mascall Formation paleoecosystems)</u>

The 16 to 12 million-year-old Mascall Formation paleoecosystems continue the record interrupted by the Columbia River Basalts. A good view of the Mascall layers can be had at the overlook south of the monument’s entrance to the Sheep Rock Unit (Figure 1.12). The lower beds of the Mascall include lake or forested swamp deposits with abundant leaf fossils described in the mid 1900s. Chaney (1925) initially suggested an ecosystem like that of the northern coast of California. He later altered this interpretation, comparing it to perhaps a deciduous forest more like the Ohio River Basin or Szechuan Province in China (Figure 5.11) (Bestland and others, 2008). The paleosol data portray a more Mediterranean climate, with a dry, warm summer and cool or cold winters for the Mascall ecosystems (Bestland and others, 2008). Some paleosols are actually similar to those found in the lower John Day Formation. This was not to last, however, as global climate cooled dramatically between 14 to 12 million years ago (Figure 5.3).

John Day Fossil Beds National Monument (Rattlesnake Formation paleoecosystems)

The Cenozoic fossil park story picks up again during the later Miocene with the Rattlesnake Formation paleoecosystems. The late Miocene Epoch, particularly around 7 million years ago, was a time of global transition, to much cooler and drier conditions. The abundant and mostly-brown paleosols of the Rattlesnake preserve three major paleoecosystems that illustrate the larger scale and global climatic changes of cooling and drying (Figure 1.13) (Retallack and others, 2002). The lower Rattlesnake (about 7.5 to 7.3 million years old) paleosols suggest a subhumid river-side woodland with scattered trees (perhaps sycamores and elms) and seasonally waterlogged meadow with about 32 to 39 inches (80 to 100 cm) of precipitation a year. From about 7.3 to 7.2 million years ago, the paleosols suggest a drier semi-arid tall grassland (20 to 33 inches or 50 to 85 cm of annual precipitation). This is the first evidence for tall grasslands—like those of the Great Plains—in Oregon (Figure 5.11). Middle Rattlesnake soils are actually quite similar to modern soils outside the park near Dayville. Climate continued to dry from 7.2 to 7.1 million years ago as semi-arid shrubland expanded as precipitation dropped to between 8 and 24 inches (20 and 60 cm), the lower end of which is comparable to what the area receives today.

Pliocene Epoch: The 3 to 4 million-year-old paleoecosystems of Hagerman Fossil Beds NM record a transitional time during the Pliocene as climate continued cooling and drying, leading to the "ice ages."

The Pliocene Epoch was of short duration—only 2.7 million years from 5.3 to 2.6 million years ago[4]—but nonetheless experienced significant global climatic changes. Following a brief warming period at the Miocene-Pliocene boundary about 5.3 million years ago (Figure 5.3), global climate began its steady march toward the “ice age” climates of the Pleistocene Epoch. The changing climate supported the expansion of steppe and grassland environments around the world. Also during the Pliocene, hominids—early human ancestors—diversified greatly. The first fully bipedal hominids of

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[4] In August of 2009, the International Commission on Stratigraphy (2009) approved a boundary change moving the Pliocene-Pleistocene boundary from 1.8 million years ago to 2.6 million years ago.

East Africa, including 3.2 million-year-old *Australopithecus afarensis* ("Lucy") (Walter, 1994), evolved during this time of cooling climate. While glaciers may have been present at the Arctic (North Pole) since the middle Miocene or earlier, the Arctic ice cap was in place by about 3.2 million years ago and the Antarctic ice sheet expanded close to its present size (Zachos and others, 2001). According to this interpretation, large ice sheets have been present at both poles for just the past 3.2 million years. Hagerman Fossil Beds NM is the only one of the Cenozoic fossil parks preserving Pliocene ecosystems (Figure 5.12). At about 4 to 3 million years old, the Hagerman Fossil Beds NM paleoecosystems existed at the same time as "Lucy" and the beginnings of the Arctic ice cap.

<u>Hagerman Fossil Beds National Monument</u>

The youngest paleoecosystems of the Cenozoic fossil parks are revealed by the lake, marsh, and river sediments associated with ancient Lake Idaho and preserved in Hagerman Fossil Beds NM (Figures 1.22 and 5.12). Leopold and Wright (1985) interpreted a pine woodland or open forest with some grassy steppe-like vegetation for Hagerman's paleoecosystem. Rocks and fossils from the middle and upper layers—including the Hagerman Horse Quarry—reflect a more open landscape, perhaps with a wet winter/dry summer climate. As might be expected with a dry season, the mass mortality of horses preserved in the Hagerman Horse Quarry may have been associated with a prolonged period of drought; the remains were buried shortly thereafter by a flash flood (Richmond and McDonald, 1998; Ruez, 2006). During Hagerman time, global temperatures were cooler than that of any Cenozoic fossil park. Smith and Patterson (1994) suggest approximately 52°F (11°C) for the mean annual temperature—very close to today's value.

Why did climate change during the Cenozoic?

The Cenozoic fossil parks contain layer upon layer of evidence that Earth's climate cooled and dried from the time of Fossil Butte NM 52 million years ago to Hagerman Fossil Beds NM 3.2 million years ago. What was driving these changes? Some visitors think that perhaps North America was closer to the equator. In fact, the Cenozoic fossil parks were farther north than they are today (Box 5.5) Paleontologists and geologists continue to research the mechanisms behind Cenozoic climate change. Increasingly precise dating techniques (like the argon-argon technique in Chapter 3) are providing a clearer chronology to better study cause and effect, called "forcing" and "response" when discussing climate change. Earth's climate is a complex system resulting from forcing and feedback (how a response can further amplify or reduce the forcing affect) between the atmosphere, ice, oceans, land surface, and living things (Ruddiman, 2001).

At a very basic level, Earth's climate is controlled by two major factors: how and how much energy from the sun (called **insolation** for *in*coming *sol*ar radi*ation*) is received and distributed around the globe, and how much of it is retained by Earth's atmosphere. Home heat pumps, refrigerators, and car air conditioners—a common tangible for summer-time visitors to the Cenozoic fossil parks—offer a simple analogy. Heat pumps, refrigerators and air conditioners work by using a fluid (liquid or gas) to transfer heat (Box 5.6). In the case of your refrigerator and air conditioning, they transfer heat from inside to outside (Figure 5.13). Heat pumps work in either direction, depending on the season: moving heat indoors during the winter and outdoors during the summer. On a global scale, oceans and the atmosphere function as heat-transferring fluids. Oceans have a much higher heat capacity and can transfer heat much more efficiently than masses of air. Changes in circulation patterns, particularly in the ocean, have an effect on how heat energy is moved around the planet. The amount of heat retained by the atmosphere, similar to the climate-controlling walls of your refrigerator, is the other major component of the global climate (Chapter 7). Variations in both of these factors have been implicated in creating the overall pattern of global climate change during the Cenozoic.

Oceans and atmosphere transfer the heat

Oceanic currents are fueled by differences in temperature, density, and salinity that together drive “conveyor belts” of water throughout the world’s oceans. Air currents are driven by differences in temperature or pressure. The position and orientation of continents, mountain ranges, and oceans present physical barriers to these currents. Over very long time periods (tens of millions of years) plate tectonics alter those physical barriers.

The establishment of ice sheets in the Southern Hemisphere 34-33 million years ago and the Northern Hemisphere 3.2 million years ago have both been linked to changes in ocean circulation patterns around Antarctica and the formation of the isthmus of Panama, respectively. The onset of large-scale glaciations (and global icehouse climate) on Antarctica may be tied to the development of a cold-water current encircling the continent. The separation of Antarctica from Australia and South America was required for such a current to form (Figure 5.14) (Kennett, 1977). The final closure of the Isthmus of Panama about 3 million years ago between Central and South America routed warm, salty water northward toward the poles (this is the so-called “Gulf Stream” current). Such a current could reduce sea ice formation, in turn providing more moisture for the formation of terrestrial ice on Greenland (Bartoli and others, 2005). Computerized climate models suggest that reduction in CO_2 concentrations between 34 and 33 million years ago, and at about 3 million years ago may have played a more significant role in the formation of large ice sheets at the poles (Liu and others, 2009; Lunt and others, 2008).

Closer to the Cenozoic fossil parks, the formation of mountainous barriers influenced the atmospheric transport of heat and water (precipitation). In Oregon and Washington today, the Cascade Range (subduction zone volcanoes, see Chapter 4) creates a pronounced **rain shadow**. The semi-arid modern ecosystems of John Day Fossil Beds NM, east of the Cascades, receive only 11 inches (28 cm) of precipitation a year. West of the range, rainforests along the coast receive as much as 100 inches (250 cm) or even 200 inches (500 cm) of precipitation per year. Those values are similar to the estimated precipitation of the Clarno paleoecosystems 44 million years ago (Retallack and others, 2000). The onset of the pronounced Cascades rain shadow coincided with the beginning of a period of rapid uplift of the range beginning about 7 million years ago—the time of the Rattlesnake Formation's semi-arid grasslands (Kohn and Fremd, 2007).

Greenhouse gasses keep the heat

Increased concentrations of greenhouse gasses allow the atmosphere to retain more of Earth's heat energy. High concentrations of carbon dioxide (CO_2) have been linked to times of globally warm climate for the past 542 million years (Royer, 2006; Ruddiman, 2001; Zachos and others, 2001,2008). This has been measured directly using bubbles trapped in ice sheets for the past 800,000 years (Chapter 7) and indirectly using estimates based on indirect physical evidence called "proxies" (the same word root as "approximation") for earlier time periods. Such proxies includes stable carbon isotopes in paleosols (Box 5.3), stable carbon isotopes of organic materials found in fossil algae, stable carbon isotopes of fossil liverworts (non-vascular plants), stable boron isotopes in marine carbonate rocks such as limestone, and stomata density in plants (Box 5.2) (Royer, 2006 and references therein).

Greenhouse gas concentrations, particularly CO_2, are thought to play a major role in the global greenhouse and icehouse climates recorded in the Cenozoic fossil parks. The greenhouse ecosystems of Fossil Butte NM, John Day Fossil Beds NM, Badlands NP, and Florissant Fossil Beds NM existed during times of high CO_2 concentrations, although the estimates of just *how* high are quite variable. Depending on the proxy, estimates range from about 300 parts per million (ppm) to more than 2,000 ppm, with widespread evidence of concentrations higher than 500 or 1,000 ppm (Royer, 2006; Zachos and others, 2008). The most dramatic example of rapid global warming during the Cenozoic occurred 55 million years ago—check out the spike on Figure 5.3! The so-called "Paleocene-Eocene Thermal Maximum" occurred prior to the Cenozoic fossil park paleoecosystems, but may provide an example of the impact a rapid influx of greenhouse gas (methane, in this case) can have on global temperature and climate (Box 5.7).

A reduction in CO_2 is thought to have played a role in cooling climate enough to support the growth of a large ice sheet in Antarctica between 34 and 33 million years ago (Liu and others, 2009; Pearson and others, 2009). Carbon dioxide concentrations rose during the warming at the end of the Oligocene (prior to 25 million years ago) and then began to decrease. During the icehouse climates of the Miocene and Pliocene, they remained generally below the 500 ppm level suggested by Royer (2006) as a threshold for the support of large ice sheets. One exception may be during the middle Miocene climatic optimum, which coincides with Columbia River Basalt eruptions and early Mascall paleoecosystems at John Day Fossil Beds NM. Paleosol evidence suggests CO_2 may have risen to double or quadruple pre-industrial levels of CO_2 (Sheldon, 2006), perhaps in response the enormous Columbia River Basalt eruptions with the Columbia River Basalts. Some other CO_2 proxies suggest levels lower than those interpreted from paleosols during the middle Miocene climatic optimum (Royer, 2006).

Geologists and paleontologists are still trying to determine what caused the long-term (tens of millions of years) decrease of CO_2 during the Cenozoic Era. Researchers have looked to long-term plate tectonic processes and their influence on either slower input or faster removal of CO_2. Two common hypotheses are summarized by Ruddiman (2001). One hypothesis suggests changes a decrease in the rate of seafloor spreading, subduction and associated volcanism would decrease the input of volcanic CO_2 and other greenhouse gasses into the atmosphere. Such a slow-down occurred until about 15 million years ago and may have contributed to a lowering of CO_2 concentrations prior to that time. After 15 million years ago, spreading rates and volcanism *increased*. But, as shown on Figure 5.3, this was a time of global cooling rather than warming as would be expected. Raymo and Ruddiman (1992) hypothesized that the Cenozoic uplift of the Tibetan Plateau and the Himalayas—already the tallest mountains in the world, they are still forming as India collides with Asia (Figure 5.14)—would have provided huge quantities of eroded material for chemical weathering. Chemical weathering of silica-rich rocks removes carbon dioxide from the atmosphere and may have contributed to the observed decrease in CO_2. The associated mechanisms, feedbacks, and responses associated with the "uplift weathering hypothesis" are still being studied and debated.

Retallack (2001, 2009) presents an alternative view that grasslands not only took advantage of the cooling and drying climate, particularly of the past 35 million years, but may have been a product of their own success. As grasslands expand, they promote increased aridity with a lower transpiration rate (meaning drier air and moister soil) than woodlands. Grassland soils promote CO_2-consuming weathering processes. They also have a higher albedo (reflectiveness) than woodlands and as grasslands expanded over more of Earth's surface, they reflected more solar warmth back toward space. All of these processes would contribute to climatic cooling and drying—and the further expansion of grassland ecosystems.

Interpreting the Changing Climates of the Cenozoic Fossil Parks

The Cenozoic Era was one of the few times in Earth history when climate transitioned between a greenhouse and an icehouse (Figure 5.2). Each of the Cenozoic fossil parks records a particular chapter of this change allowing interpreters to place their park into Cenozoic climatic context. You do not need to deliver an entire program on Cenozoic climate change. There are many opportunities to incorporate this information into other interpretive opportunities. For example, the park videos at John

Day Fossil Beds NM, Agate Fossil Beds NM, and Hagerman Fossil Beds NM each require park staff to "push play," and most interpreters give a brief introduction to the video. I would take advantage of this interpretive opportunity to mention that the park is one of six that tell the story of a great transformation in climate from the world of the dinosaurs to the world of wooly mammoths (Box 3.6). The terms "greenhouse" and "icehouse" provide a simple method of designating the basic climate states during such an introduction, and in other interpretive opportunities. Utilizing the park's state fossil to connect to a greenhouse or icehouse climate may also connect with a visitor's sense of place regarding their home (Figure 5.10). Being surrounded by evidence of natural climate change provides ample opportunity to engage visitors on modern climate change and its impact on our current and our grandchildren's future ecosystems and the animals and plants that live there. The Cenozoic fossil parks also provide opportunities to interpret a warmer world with CO_2 concentrations higher than today, but within projected values of the coming decades and centuries. Ecosystems from those time periods are very different from what we are used to today (Figures 5.8, 5.9, 5.11, and 5.12). Interpreting modern climate change is further discussed at the end of Chapter 7. Climate change lead to the expansion of grassland ecosystems—a common tangible for visitors travelling through the West—at the expense of nearly-tropical forests. The rise of grasslands is an integral part of the horse family history (Chapter 6).

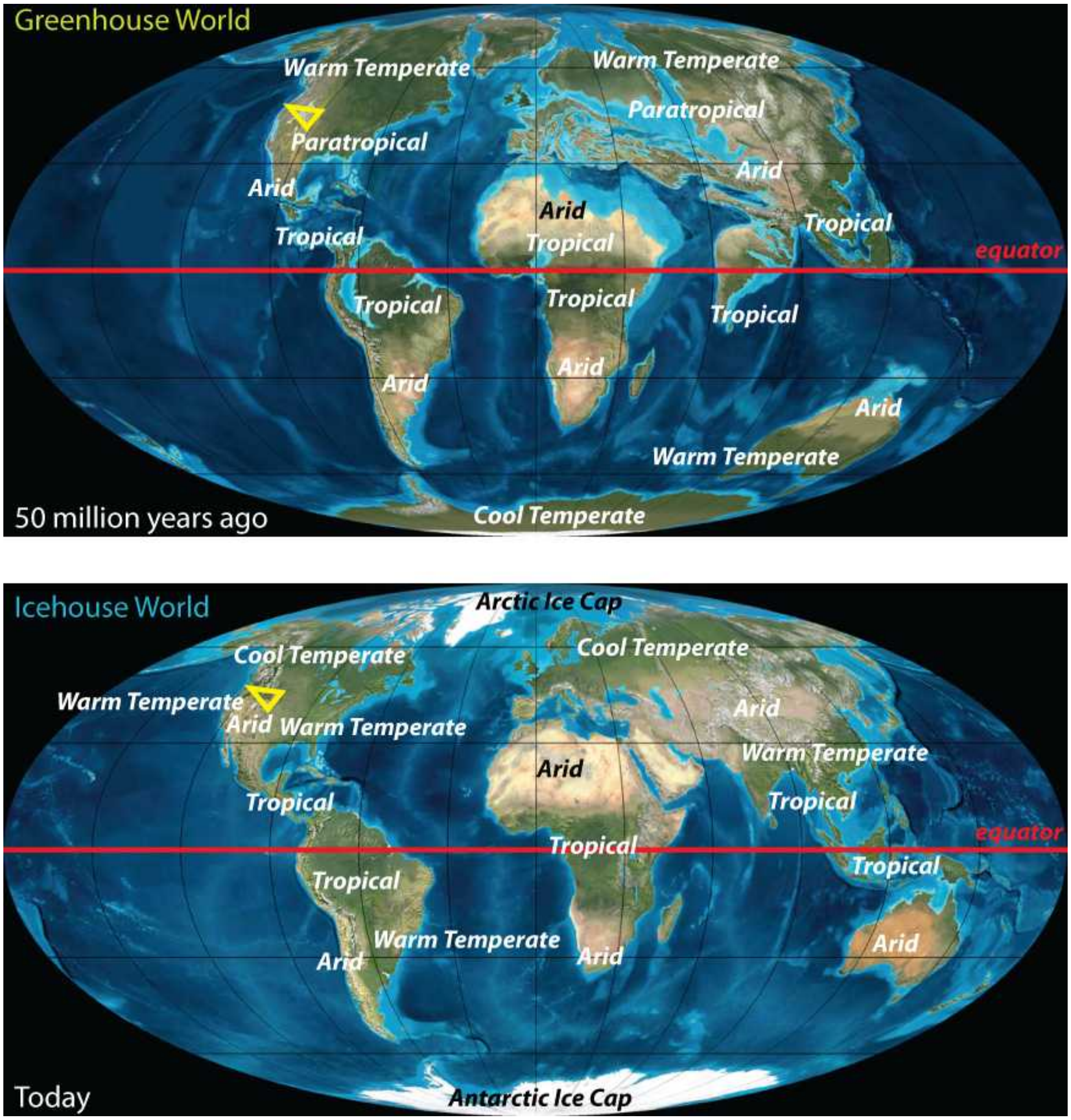


Figure 5.1. Distribution of climate zones on a "greenhouse" world (50 million years ago, during the Eocene) compared an "icehouse" world (today). During greenhouse periods, there are little or no ice caps at either pole and warm temperate climates exist at relatively high latitudes. During icehouse periods, ice caps are present at one or both poles and warm temperate climates are not found at high latitudes. Yellow triangle outlines the area of the Cenozoic fossil parks. "Paratropical" climates have average annual temperatures between 68 and 77°F (20 and 25°C) while tropical climates experience average annual temperatures above 77°F (25°C) (Wolfe, 1979). (Eocene climatic distribution based on information from Scotese [2002]. Modern climatic distribution based on information from Kottek and others [2006]. Paleogeographic maps modified from and used with permission of Ronald Blakey, Northern Arizona University Department of Geology.)

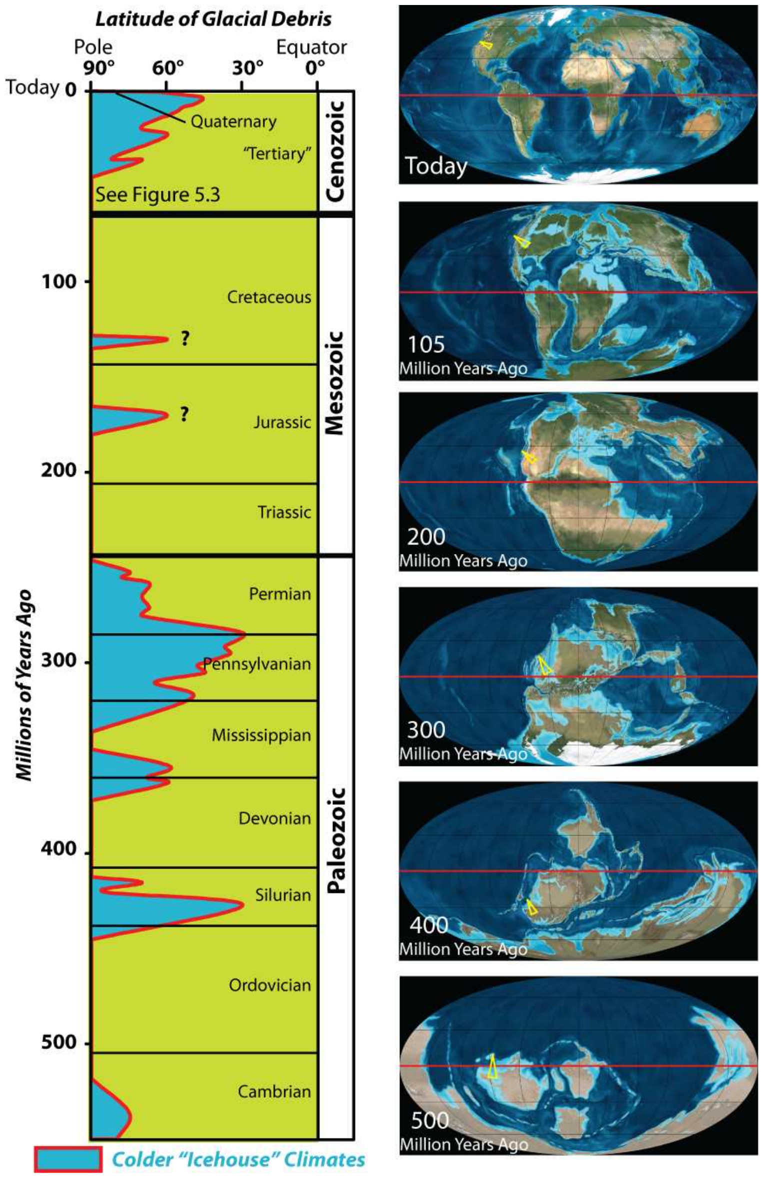


Figure 5.2. Earth's climate can be broadly categorized as "greenhouse" or "icehouse" conditions (Figure 5.1). The graphic on the left shows timing and latitudinal distribution of ice rafted debris and other evidence of glaciers during the last 540 million years. Their presence at increasingly lower latitudes, closer to the equator, indicate increasingly colder climates. The paleogeographic maps on the right show the distribution of continental landmasses during the same time period. Note the ice caps during icehouse conditions. Also note that the greenhouse-icehouse transition during the Cenozoic is one of just a few such shifts—this is only the third time in the past 542 million years Earth has been this cold! The yellow triangles outline the area of the Cenozoic fossil parks. (Ice sheet figure modified from Lillie [2005], compiled from information in Frakes and others [1992]. Paleogeographic maps modified from and used with permission of Ronald Blakey, Northern Arizona University Department of Geology.)

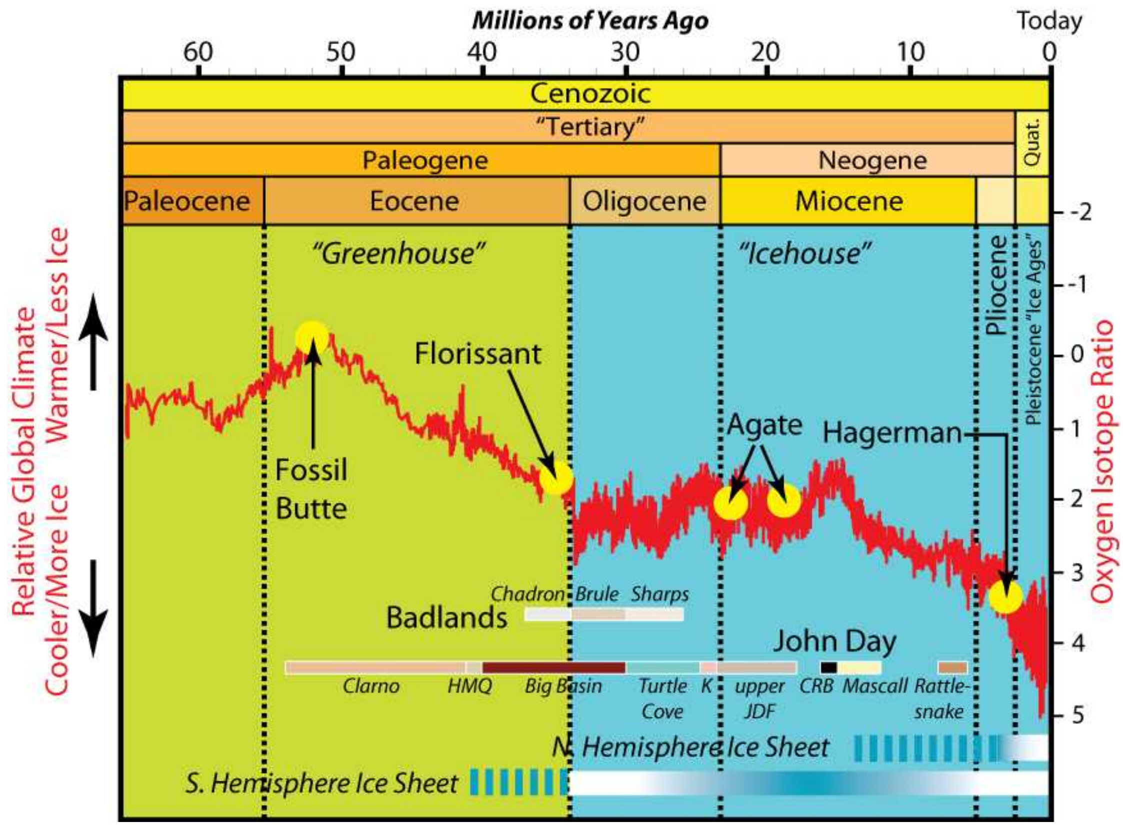


Figure 5.3. The Cenozoic fossil parks track the pulse of Earth's climate over the past 65.5 million years (Cenozoic Era)—the most recent time Earth transitioned from "greenhouse" to "icehouse" conditions. This climate graph is based on oxygen isotopes from deep-sea Foraminifera fossil shells (Box 5.1). The age of fossils in the Cenozoic fossil parks is indicated on the graph. Because Badlands NP and John Day Fossil Beds NM span longer periods of time, the bars below the climate graph show the time period spanned by the various formations and fossil assemblages. HMQ= Hancock Mammal Quarry; K = Kimberly Member of the John Day Formation; JDF = John Day Formation; CRB = Columbia River Basalts. The presence or potential presence (dashed lines) of ice sheets at the North and South poles is also indicated. Times of increased ice cover are indicated by whiter shades (Oxygen isotope data from Zachos and others [2008]. Updated oxygen isotope data downloaded from http://www.es.ucsc.edu/~jzachos/Publications.html, accessed November, 2009.)

Digging Deeper Box 5.1. ***Tiny forams are giant contributors to global climate records.***

Since the 1950s, scientists have looked to a somewhat surprising source for information on past climates: oxygen isotopes recorded in the "shells" of tiny fossils buried in deep-sea mud. The fossils in question, Foraminifera (or "forams" for short) are single-celled, amoeba-like microorganisms that produce a "shell" called a test. Think of them as "armored amoebas." Although generally quite small (many are microscopic, some can reach a few inches in diameter), they are fantastically abundant and found throughout the world's oceans. You may have seen them before—the Great Pyramids of Egypt are constructed of limestone composed almost entirely of coin-sized, Eocene-aged forams! For a refresher on isotopes and atoms, see Box 3.3.

There are two main isotopes of oxygen: oxygen-18 and oxygen-16. Oxygen-18 (^{18}O) is heavier while oxygen-16 (^{16}O) is lighter and much more common, making up 99.8% of all oxygen. The ratio of ^{18}O to ^{16}O in foram tests is dependent on both temperature of the surrounding water (two hydrogens and an oxygen make H_2O) and the presence and size of polar ice sheets. Changes in the ratio over time create a combined record of changes in ocean temperature and ice sheet size making them an excellent recorder of global climate. Figure 5.3 was created using foram oxygen isotope data, and compared to a standard. It is multiplied by 1000 to make the small numbers easier to use. The numbers -2 through 5 on Figure 5.3 are these oxygen isotope ratios. The oxygen isotope ratio is denoted $\delta^{18}O$ (pronounced "delta O-18") and calculated using the following equation:

$$\delta^{18}\mathrm{O} = \frac{\left(\frac{^{18}O}{^{16}O}\right) sample - \left(\frac{^{18}O}{^{16}O}\right) standard}{\left(\frac{^{18}O}{^{16}O}\right) standard} \times 1000$$

The isotope ratio in the shell is directly proportional to the temperature of the surrounding water so that for each 7.6°F (4.2°C) decrease in water temperature, the oxygen isotope ratio increases by 1. During the Eocene cooling (Figure 5.3), oxygen isotope ratio increased by nearly 2, suggesting a cooling in deep-sea water of 15°F (8°C). Since there were no ice sheets present, the increase in oxygen isotope ratio was due solely to cooling of deep-sea water, indicative of global climate cooling (Zachos and others, 2001).

Changes in ice volume have a dramatic effect on oxygen isotope ratios. How? It's all about weight. As water vapor evaporates from the oceans and rises, the heavier oxygen isotope (^{18}O) preferentially "falls out" in rain (you would put down that heavier bag of groceries first, too) (Figure 5.4). As water vapor travels from the equatorial region to the poles, this process repeats itself, with more and more of the ^{18}O falling out with rain. This process leaves precipitation at the poles very depleted in ^{18}O. When there are no ice sheets at the poles locking up water, the rain eventually ends up back in the ocean and the overall ratio does not change. However when large ice caps are present, they lock up enormous quantities of ^{18}O depleted water and prevent it from returning to the ocean. Hence, the oceans become enriched in ^{18}O, increasing the oxygen isotope ratio. Thus for the icehouse portion of Figure 5.3, the increase in oxygen isotope ratio reflects a combination of changes in deep-sea water temperature and changes in ice volume.

Deep-ocean sediments provide an excellent record of global climate because the deep ocean does not experience the large seasonal, latitudinal, and geographic variations in temperature that affect the surface of the ocean and terrestrial climate records (Lear and others, 2000). The deep-sea record also benefits from nearly continuous deposition, a large data set of cores; such cores are globally correlated and dateable with high resolution (Zachos and others, 2008; Zachos and others, 2001). The oxygen isotope record is considered an excellent archive of the pulse of global climate and provides a framework to compare and connect the terrestrial climates of the Cenozoic fossil park paleoecosystems. Not a bad legacy for an armored amoeba!

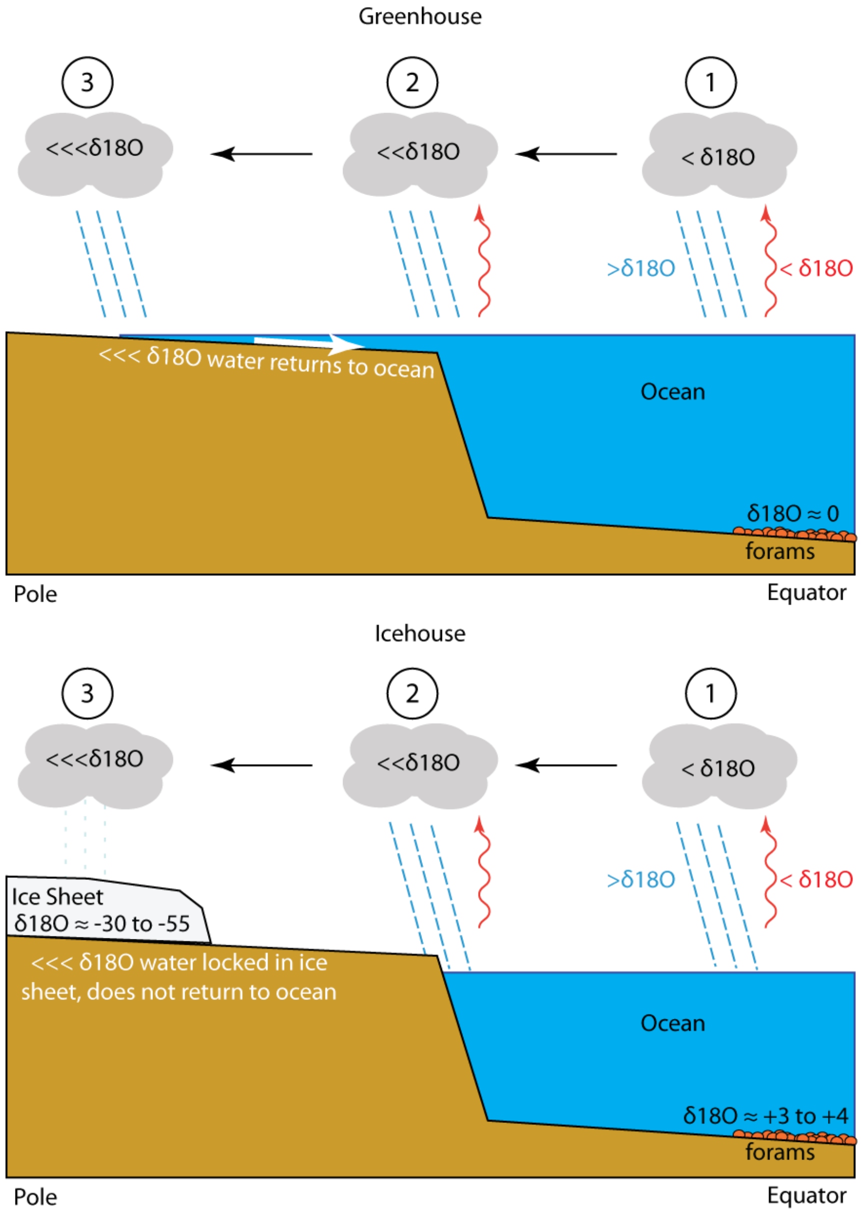


Figure 5.4. Tiny fossils can record big changes in climate. The oxygen isotope ratio ($\delta^{18}O$), in the "shells" of fossil forams records both the temperature of deep-sea water and the presence of large ice sheets (Box 5.1). As water evaporates near the equator, the rising water vapor is depleted in heavier ^{18}O (indicated by $< \delta^{18}O$). Once the water vapor condenses into clouds and rain, much of the ^{18}O that is present "rains out," further depleting the water vapor in ^{18}O (giving a more negative $\delta^{18}O$ value, indicated by $<<< \delta^{18}O$). This cycle repeats itself numerous times at higher and higher latitudes until water at the poles has very little ^{18}O. With no ice sheet, the water returns to the ocean. When there is an ice sheet, the ^{18}O-depleted water is locked up at the poles, leaving the oceans very rich in ^{18}O (giving a more positive $\delta^{18}O$ value). Over time, the forams are buried. New forams then record changes in temperature and ice volume, creating a time capsule of climate records on the sea floor. (Redrawn after Ruddiman [2001] and Prothero[2006].)

***Digging Deeper Box 5.2*. Ancient climate "leaves" behind plant fossil evidence.**

When compared to the relatively stable conditions on the bottom of the sea (Box 5.1), estimating ancient climates on land is much more challenging. As discussed by Wolfe (1993, 1994), terrestrial temperatures can vary over a wide range not only seasonally, but daily. Precipitation is not constant and varies seasonally. Through all these changes, plants are rooted in place and must tolerate such variable conditions—they can't easily move to Florida when it gets cold! Paleontologists have thus turned to plant fossils (leaves, fruits, nuts, stumps, and even pollen) for clues to ancient climates.

Qualitative analyses, using relative comparisons, of fossil plant, leaf, wood, and pollen assemblages to modern representatives of the same family genus or species, are commonly the first methods used to study past and present ecosystems. One of the first questions paleontologists ask is: "Where on Earth are similar communities of plants found?" Very careful taxonomic study and the assumption that modern climatic tolerances of the plants in question were similar in their past tolerances are major assumptions—that may or may not be valid—associated with this methodology (Boyle and others, 2008; Manchester, 1994; Meyer, 2003). Nevertheless, some plants are indicative of broad-scale climate interpretations; for example, the palm tree suggests frost-free climates.

Plant fossils are also tools for quantitative (numerical) estimation of past climates. One of the simplest quantitative methods is Leaf Margin Analysis (Wilf, 1997; Wolfe, 1978, 1979). For nearly 100 years, scientists have recognized the very strong relationship between leaf shape and temperature (Figure 5.5). The percentage of species with smooth-edged leaves is directly proportional to the average annual temperature (or "MAT" for Mean Annual Temperature). In other words, forests with higher percentages of plant species with smooth-margined leaves experience higher MAT. Conversely, forests with higher percentages of toothed-leaf (jagged-edged) species experience lower mean annual temperature. In addition to leaf teeth, other features can also be used to broadly characterize climate. Leaves in warmer and wetter climates tend to be larger and thicker than their colder and drier counterparts. Warm-climate leaves also often have a "drip tip" at the leaf's apex.

This technique has been applied to fossil forests of John Day Fossil Beds NM (Manchester, 1994; Meyer and Manchester, 1997) and Florissant Fossil Beds NM (Meyer, 2001) (Figure 5.5). An upcoming (2010) publication will contain Leaf Margin Analysis data for Fossil Butte NM (A. Aase, NPS paleontologist, personal communication, 2009). Why this relationship is so strong is a question scientists have attempted to answer for decades. One recent hypothesis is that toothed leaves allow greater surface area for gas exchange early in the growing season, when water and nutrients are plentiful, but temperature is cooler. Cooler temperatures tend to slow down chemical reactions (we all move a bit slower in the winter!), so the increase in surface area would help offset this sluggishness (Royer and Wilf, 2006).

The simplicity of this technique is a major plus: simply count the number of species of toothed leaves (or smooth-margined leaves) divide by the total number of species and plug into an equation or plot on a graph to estimate the ancient climate. This is an effective tool to use with visitors, because in just a few minutes of counting actual fossil leaves, they can estimate past climate…without a degree in botany or paleontology. The technique also does not rely on proper taxonomic assignments which can change depending on individual paleontologists' interpretations.

(*continued on next page*)

Digging Deeper Box 5.2 (continued). ***Ancient climate "leaves" behind plant fossil evidence.***

Paleontologists have developed increasingly sophisticated shape analyses that look at more than just the leaf margin (or edge). Climate-Leaf Analysis Multivariate Program, or CLAMP (Wolfe, 1993) assesses 31 leaf shape and size variables in an attempt to increase accuracy and precision and provide more detailed climate estimates including mean annual range of temperature (MART) and mean annual precipitation (MAP) in addition to mean annual temperature (MAT). Digital technology and analysis has increasingly contributed to this effort (Royer and others, 2005).

Plant fossils can also provide important clues for estimating other climatic conditions, such as carbon dioxide concentrations. The number of openings (called "stomata", think of them as the leaves' "doors") on leaves tends to increase with lower carbon dioxide levels. Since plants require carbon dioxide for photosynthesis, if concentrations are higher, they can have less openings. Lower concentrations require more openings to obtain the same amount of carbon dioxide. Plants try to minimize the number of stomata, because just like having open doors or windows in your house during the winter lets the heat out, having lots of stomata can cause the plant to lose water vapor every time the "door" is opened.

The other three Cenozoic fossil parks (Agate Fossil Beds NM, Badlands NP, Hagerman Fossil Beds NM) do not preserve leaf fossils, so climatic information is obtained through other methods such as paleosol reconstructions at Agate Fossil Beds NM and Badlands NP, or fossil pollen analysis at Hagerman Fossil Beds NM.

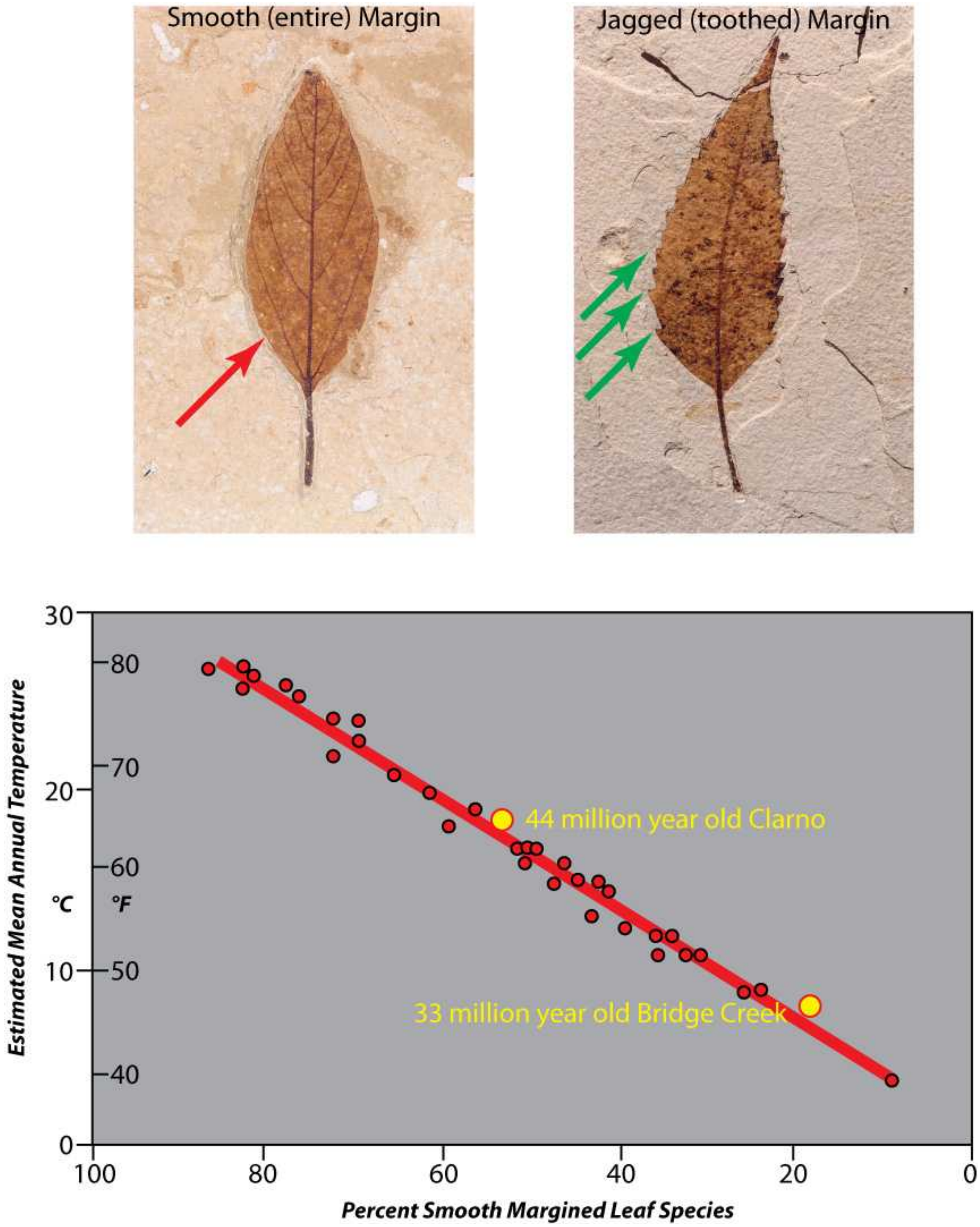


Figure 5.5. Leaf shape is a clue to past climates. Since the early 1900s, botanists have noticed the strong relationship between higher percentages of leaf species with smooth margins (red arrow) and no "teeth" (green arrows) and higher mean annual temperature. This relationship is utilized in the Leaf Margin Analysis technique, commonly applied to fossil leaf assemblages including those from the Bridge Creek and Clarno paleoecosystems at John Day Fossil Beds NM. More sophisticated description of different leaf shape characteristics are used, but Leaf Margin Analysis is still a good first approximation of past climate. (Graph after Wolfe [1979] with Clarno and Bridge Creek values from Manchester [1994] and Meyer and Manchester [1997]. Leaf photos are courtesy Arvid Aase [Fossil Butte NM]).

<u>Digging Deeper Box 5.3</u>. Fossil soils provide the "dirt" on ancient climates and ecosystems.

An ecosystem's plants are rooted in soil, while its animals walk upon or burrow into it. The soil is the interface between an ecosystem's plants and animals and the underlying rock layers. Soils that are preserved in the geologic record are called **paleosols**. Paleontologists describe and analyze paleosols to gather information on past climates (Retallack and others, 2000). Paleosols are particularly useful because not all paleosols preserve plant or animal fossils, but most contain at least basic information about past climates. Paleosol description, chemical analysis, and comparison to similar modern soils provide paleontologists the "dirt" on ancient precipitation amounts and seasonal patterns, mean annual temperature and range of temperature, as well as type and extent of vegetation rooted in the soil (Figures 5.6 and 5.7). Paleosols are particularly useful for documenting the spread of grassland paleoecosystems even though grass **macrofossils** are rather rare. Because soils can take thousands or even tens of thousands of years to form, their presence indicates a time of stability without rapid erosion or deposition.

Colors of paleosols are particularly helpful, and a readily recognizable tangible for visitors. Many of the vibrant colored bands in rocks that visitors notice at Badlands NP and John Day Fossil Beds NM are paleosols. At John Day Fossil Beds NM, deep red paleosols were much more common during the Eocene greenhouse and suggest wetter, more deeply weathered soil layers. Icehouse paleosols tend to be brown or green in color (Retallack and others, 2000). The striking red bands of the Brule Formation in Badlands NP represent open areas next to Oligocene streams in the Brule Formation (Retallack, 1983).

Because soil forms in place, successive layers of soils create a wonderful record of evolving ecosystems (and changing climate) at a locality or over a wider region (Figure 5.6). Paleosols are *in situ* tangibles (Chapter 3). They provide visitors the opportunity to view, or in some cases put their hands on, the soil surface where animals walked, insects burrowed, and plants grew millions of years ago.

Fossil soil layers are particularly well preserved at John Day Fossil Beds NM, where Retallack and others (2000) described a series of more than 435 paleosols at the Painted Hills but noted only about a dozen fossiliferous layers. Similarly, Retallack (1983) described 89 fossil soil layers from the Pinnacles area of Badlands National Park. Agate Fossil Beds NM also contains paleosols, the "Agate paleosurface" caps the ridges along the *Daemonelix* Trail (Hunt, 1990) so visitors can walk on the same soil layer as the Miocene inhabitants of the Agate Fossil Beds NM area. Various reconstructions used in Chapters 1 and 5 of the manual were developed using paleosol data.

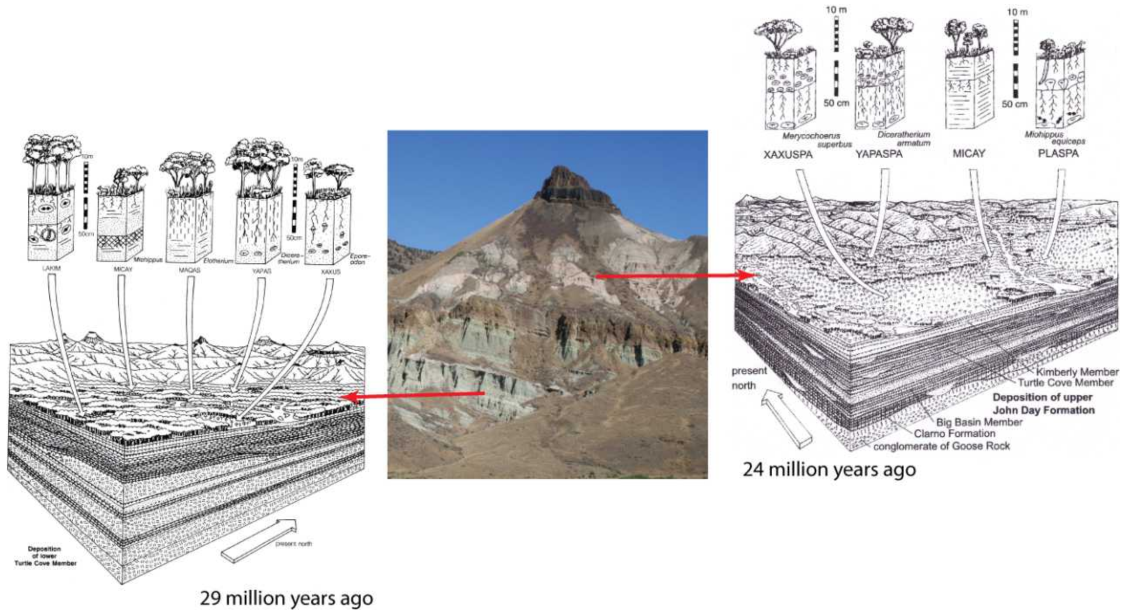
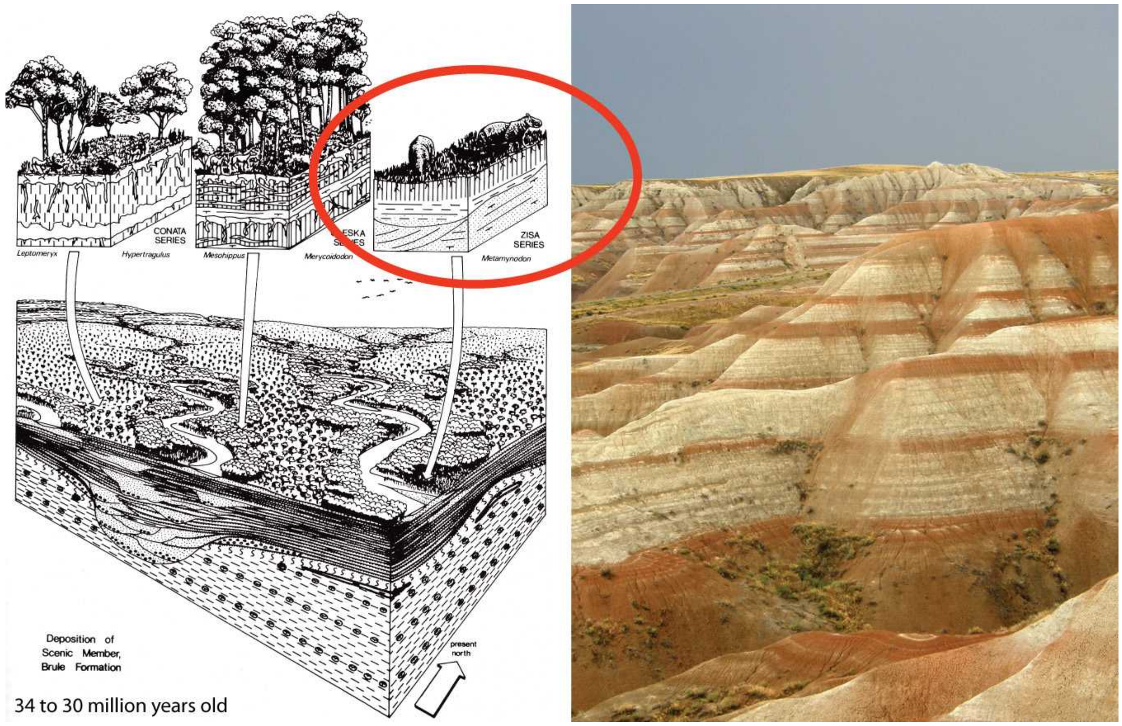


Figure 5.6. Paleosols are *in situ* tangibles illustrating changing climate and ecosystems over time at a particular locality. Changes in paleosol characteristics spanning 5 million years at Sheep Rock (John Day Fossil Beds NM) suggest such changes. Notice how paleosols of open spaces are increasingly widespread 24 million years ago (Kimberly Member) compared to those of 29 million years ago (Turtle Cove Member). The paleosol names are derived from descriptive terms of the Sahaptin American Indian language used in the Pacific Northwest (Retallack and others, 2000; Retallack, 2004). (Sheep Rock photo by Robert J. Lillie. Paleosol reconstruction from Retallack and others [2000] and Retallack [2004], reproduced with permission of Gregory Retallack and the Geological Society of America [Turtle Cove] and Elsevier publishing [Kimberly Member].)



<u>Figure 5.7</u>. Distinctive color makes paleosols an easy-to-spot tangible. Many of the red bands of the Oligocene-aged Brule Formation in Badlands NP represent open areas along ancient streams. Fittingly the paleosol name “Zisa” is derived from a Lakota word for “reddish.” (Photo by Jason Kenworthy. Paleosol reconstruction from Retallack [1983], reproduced with permission of Gregory Retallack and the Geological Society of America.)

Figure 5.8. "Eo-scenes" from the greenhouse Cenozoic fossil parks—Fossil Butte NM, John Day Fossil Beds NM (Clarno), Badlands NP (Chadron Formation), and Florissant Fossil Beds NM. During the Eocene, Cenozoic fossil park ecosystems consisted of large lakes and nearly tropical forests. (Fossil Butte NM photo of crocodile and author [in 2001!] courtesy Vincent Santucci; *Phareodus encaustus* fish photo, *Heliobatis radians* stingray photo, and palm frond photo are NPS images. Clarno Nut Beds Mural by Larry Felder for NPS, photographed by Will Landon for NPS; image of Chadron Formation with a titanothere courtesy Badlands Natural History Association; Florissant Formation mural courtesy Jeff Wolin [Florissant Fossil Beds NM].)

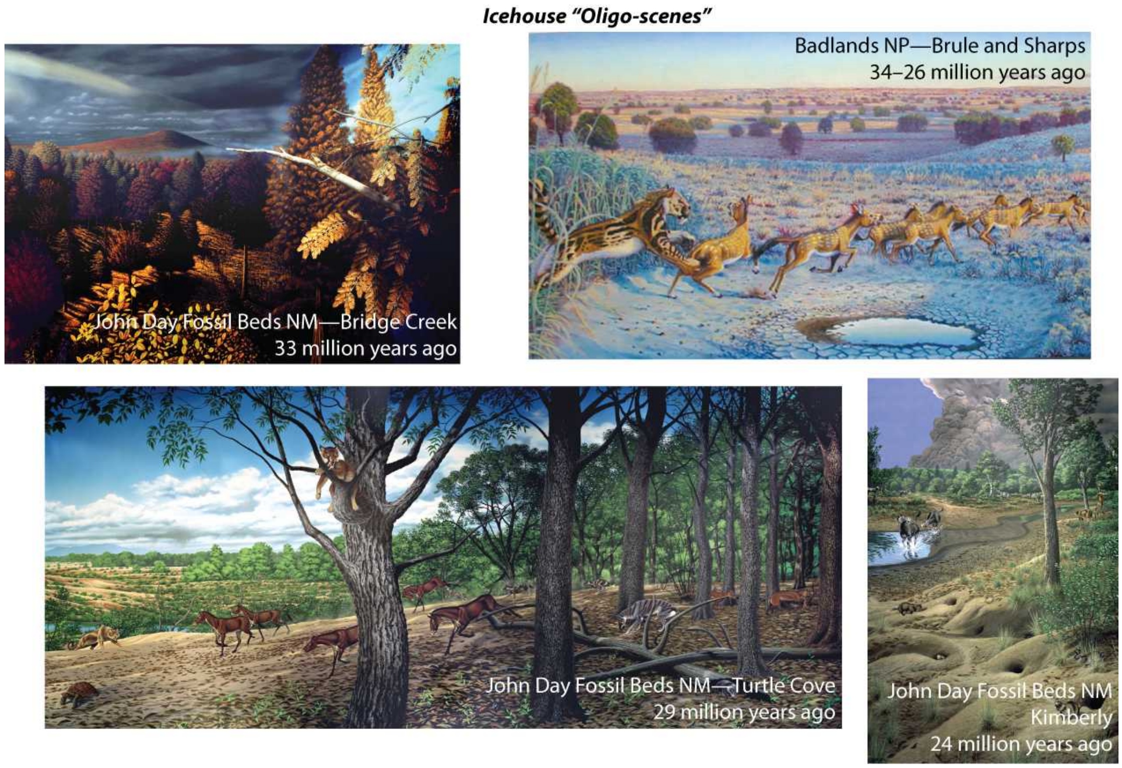


Figure 5.9. "Oligo-scenes" from the icehouse Cenozoic fossil parks of the Oligocene—John Day Fossil Beds NM and Badlands NP. The large lakes and nearly tropical forests were gone from the Cenozoic fossil parks. Those paleoecosystems were replaced by increasingly open woodlands (John Day Fossil Beds NM) and savannahs (Badlands NP) and climate cooled and dried. This cooling and drying was exacerbated in the continental interior of Badlands NP. (John Day Fossil Beds NM murals by Roger Witter for NPS, photographed by Will Landon for NPS; Mural of Badlands NP courtesy Badlands Natural History Association.)

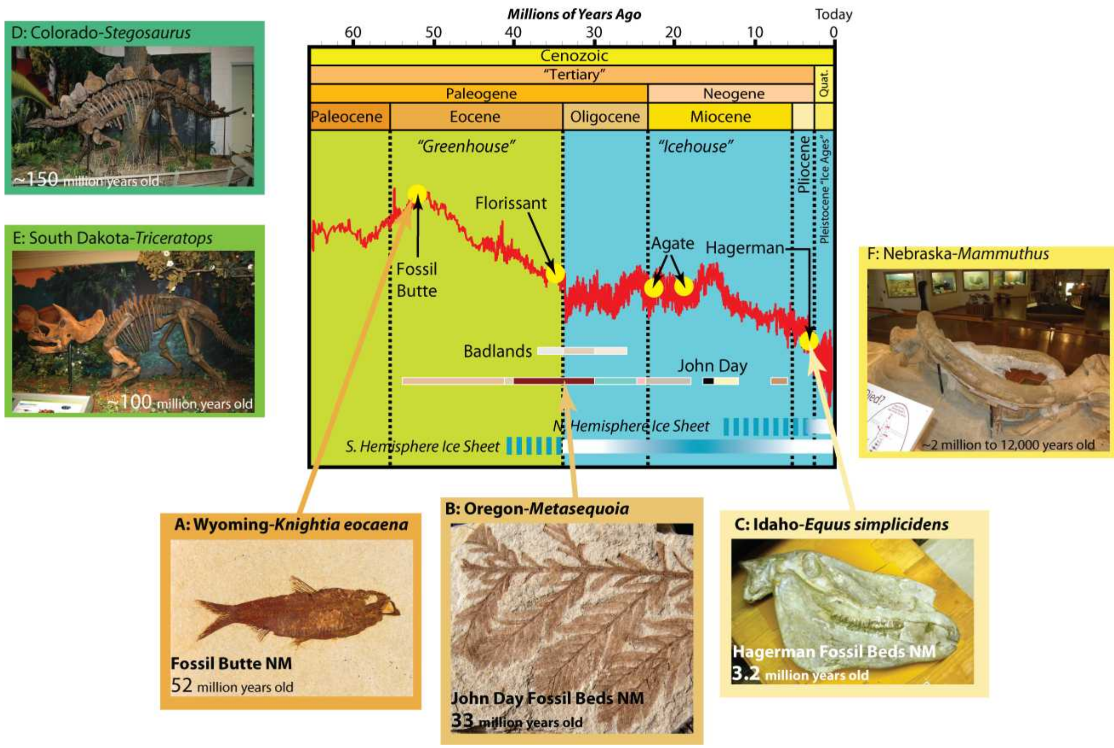


Figure 5.10. The Cenozoic fossil parks preserve a "stately" record of changing climates. Fossils from Fossil Butte NM, John Day Fossil Beds NM and Hagerman Fossil Beds NM have been designated as official "state fossils." Together, their paleoecosystems—subtropical lake, woodland, and grassy forest, respectively—speak to the cooling and drying of global climate of the nearly 50 million years they span (Box 5.4). (A: NPS photo; B: photo courtesy Ellen Morris Bishop [Oregon Paleo Lands Institute]; C: NPS photo courtesy Phil Gensler [Hagerman Fossil Beds NM]; D and E: photos courtesy Thomas Holtz [University of Maryland]; F: photo by Jason Kenworthy.)

***<u>Digging Deeper Box 5.4</u>*: “Stately” fossils demonstrate changing climates.**

Fossils from three of the Cenozoic fossil parks are designated as the official state fossil for Wyoming, Oregon, and Idaho (Figure 5.10). State fossils from Colorado, South Dakota, and Nebraska are not found in the Cenozoic fossil parks but contribute to the story of changing climates and evolving ecosystems.

Wyoming’s state fossil *Knightia eocaena* is a small, about 4 inches (11 cm) long, herring-like fish and the most common fish found at Fossil Butte NM. It may be the most abundant complete vertebrate fossil in the world. *Metasequoia glyptostroboides* (dawn redwood) is Oregon’s state fossil and abundant in the Bridge Creek assemblage at John Day Fossil Beds NM. The Hagerman Horse *Equus simplicidens* is the state fossil of Idaho and represents the oldest member of the modern horse, zebra, and donkey genus *Equus.* These state fossils illustrate global climatic changes during the Cenozoic from subtropical lakes at Fossil Butte to woodlands at John Day Fossil Beds NM to the open, grassy forests of Hagerman Fossil Beds NM.

The state fossils of Colorado (Jurassic-aged *Stegosaurus* dinosaur), South Dakota (Cretaceous-aged *Triceratops* dinosaur), and Nebraska (Pleistocene-aged *Mammuthus* mammoth) are not found in Florissant Fossil Beds NM, Badlands NP, or Agate Fossil Beds NM. However these state fossils but can also be used to illustrate climatic changes from the greenhouse world of the dinosaurs to the ice age world of the mammoths (Box 3.6).

Visitors and interpreters can take pride that the fossils of three of the Cenozoic fossil parks were chosen as icons of their respective states. Forty states have designated state fossils which are listed on various websites (visit the state government’s homepage for information on state symbols). In addition to the three from the Cenozoic fossil parks, other state fossils are found in NPS areas. Here are three more: petrified wood *Araucarioxylon arizonicum* (Petrified Forest NP, Arizona); the scallop *Chesapecten jeffersonius* (Colonial National Historical Park, Virginia); and the Petoskey Stone, a type of coral (Sleeping Bear Dunes National Lakeshore, Michigan).

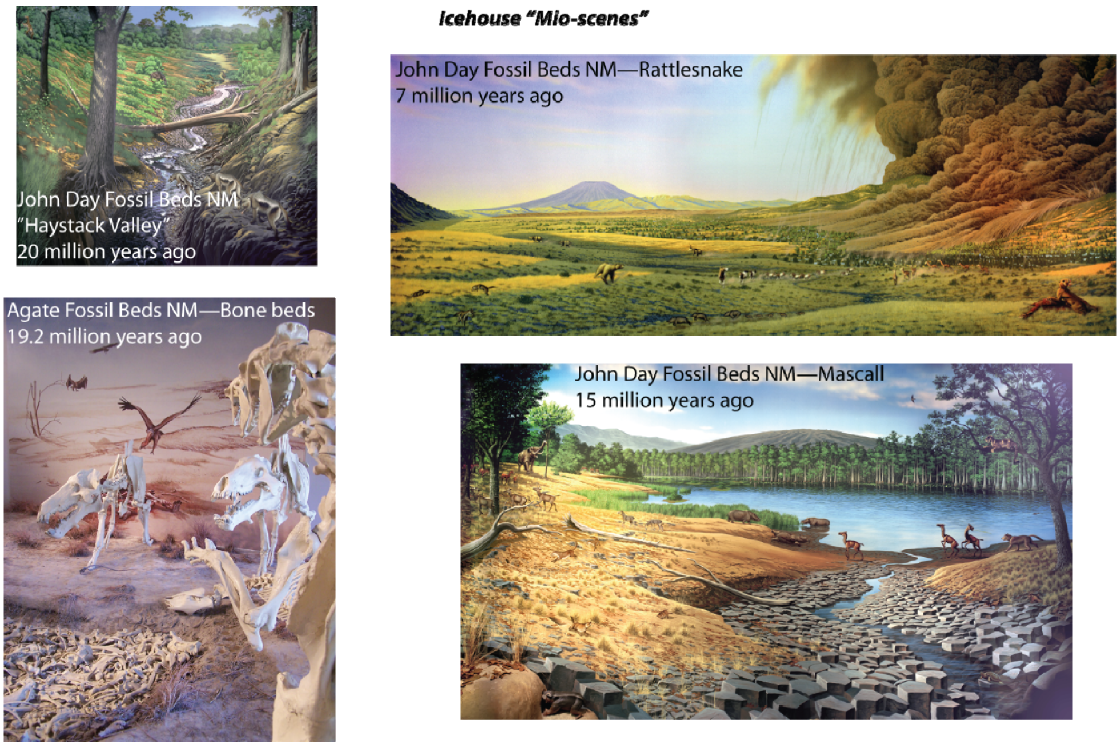


Figure 5.11. "Mio-scenes" from the icehouse Cenozoic fossil parks of the Miocene—John Day Fossil Beds NM and Agate Fossil Beds NM. During the relatively warm global climates of the Miocene savannah and grassland ecosystems spread throughout western North America and the Cenozoic fossil parks. Animals congregated and died in great numbers at watering holes like those preserved at Agate Fossil Beds NM during a time of increased global aridity, amplified by the continental interior location. By the late Miocene, the effects of the Cascade Range rain shadow were being felt in Oregon and the first true grasslands, like those of the Rattlesnake paleoecosystems, began to take hold. (John Day Fossil Beds NM murals by Roger Witter for NPS, photographed by Will Landon for NPS; NPS photo of Agate Fossil Beds NM diorama and mural.)

Icehouse "Plio-scene"

Figure 5.12. A "Plio-scene" from Hagerman Fossil Beds NM. The climates of the Pliocene were transitional between the cooling late Miocene climates to the "ice ages" of the Pleistocene. At Hagerman Fossil Beds NM, a very grassy, or steppe-like understory was found among open woodlands along the shores and streams of ancient Lake Idaho. These are the youngest paleoecosystems of the Cenozoic fossil parks. (Mural by Jay Matternes, copyright by the Smithsonian Institution. Used with permission.)

<u>Digging Deeper Box 5.5</u>. During the Eocene, North America did not go to the tropics, the tropics came to us!

When discussing the warmer climates of the Eocene, visitors sometimes ask "Were we just closer to the equator?" After all, many retirees or winter vacationers in North America head south toward the equator and warmer (less seasonal) climates! North America was closer to the warm equator at times during the Paleozoic and early Mesozoic eras (Figure 5.2 and 5.14). During the Mississippian Period (359-318 million years ago), limestones deposited in Caribbean-like seas inundated much of the continent's interior which was very close to the equator. These limestones are visible today throughout the Midwest and in the walls of many NPS caves including Jewel Cave NM and Wind Cave NM (Black Hills of South Dakota), and Mammoth Cave NP (Kentucky).

During the Cenozoic Era, North America was well north of the equator. The Cenozoic fossil parks were in fact probably even further north than they are today. Estimates of paleolatitudes for the Cenozoic fossil parks range from approximately 46°N (Florissant Fossil Beds NM, the furthest south) to 52°N (John Day Fossil Beds NM-Clarno Unit, the furthest north) 50 million years ago (Scotese, 2001). For comparison, cities near 52°N today include Calgary, Alberta; London, Berlin, and Warsaw. Today, the parks range between about 39°N at Florissant to 45°N at John Day-Clarno. Instead of North America going to the tropics, the warm climates of the tropics came to us!

<u>Digging Deeper Box 5.5</u>. Transferring and retaining heat controls climate.

Humans are very familiar with small-scale climate control devices like heat pumps, air conditioners, and refrigerators that allowing us to stay warm in your living room, comfortable in your car, and save that leftover pizza for tomorrow. These small-scale appliances can provide an analogy for the basic principles behind how heat moves through the global climate system. How do these appliances work? Fluids are used to transfer heat energy from one place to another. Air conditioners and refrigerators do not cool the air so much as they remove heat and transfer it somewhere else.

These appliances have four major components: a compressor, a set of coils that operate as a condenser (transferring heat out of the system; warming the surrounding air), an expansion valve, and a set of coils that operate as an evaporator (transferring heat into the system; cooling the surrounding air) (Figure 5.13). They are connected by pipes and coils that contain a heat-transferring fluid (called a refrigerant) that can alternate between a liquid and a gas. Let's use the refrigerator as an example. The refrigerator's compressor compresses refrigerant (as a gas) to a very high temperature and pressure. It then travels through the condenser coils (you can see them behind your fridge) where heat is dissipated out of the system (it's warm behind the fridge), condensing the refrigerant into a high pressure liquid. It travels through the expansion valve, expanding into a low pressure liquid. The low pressure liquid travels through the evaporator coils where it evaporates into a gas absorbing heat (it's cold inside the fridge) from the surrounding air. The cycle then starts again as this gas is returned to the compressor.

The system works most efficiently with a barrier between the "inside" and "outside" climates. Likewise the atmosphere plays a critical role in retaining heat energy. The refrigerator's "atmosphere" (thick door and seal) helps to maintain the desired "climate" inside. When heating or cooling our homes we keep the windows and doors shut and use insulation ("atmosphere") to maintain the desired "climate" in our house. And, as my father constantly reminded me on our family road trips, the air conditioner works best with the car's windows rolled up!

There is no compressor or expansion valve to maintain global climate. The main points to share with visitors are: 1) fluids, be they water (oceans) or air (atmosphere), transfer heat from one place to another; and 2) increased concentrations of greenhouse gasses in the atmosphere trap more of that heat energy, like a refrigerator's thick walls trap cooler air inside.

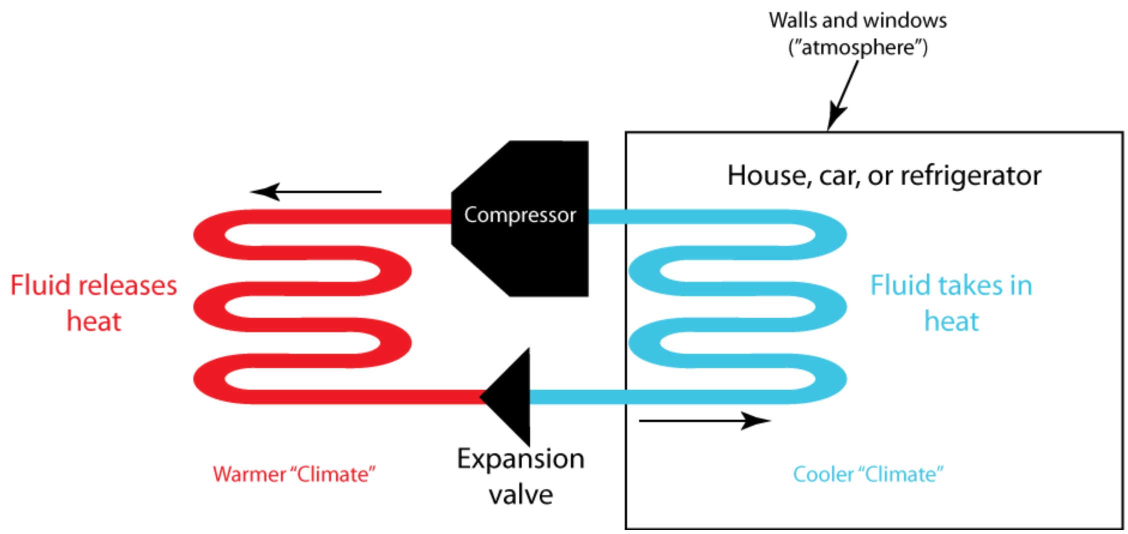


Figure 5.13. The operation of a refrigerator provides an analogy to interpret how the transfer and retention of heat affects climate (Box 5.6). Fluids transfer heat from one place to another. In your refrigerator, the condenser coils release heat from the system while the evaporator coils draw heat into the system, cooling the surrounding air. For this system to work well, a barrier must be in place to separate the warmer and cooler "climates." Earth's atmosphere is analogous to such a barrier, highlighting the importance of greenhouse gasses. Heat pumps and car air conditioners work on the same principle as the refrigerator.

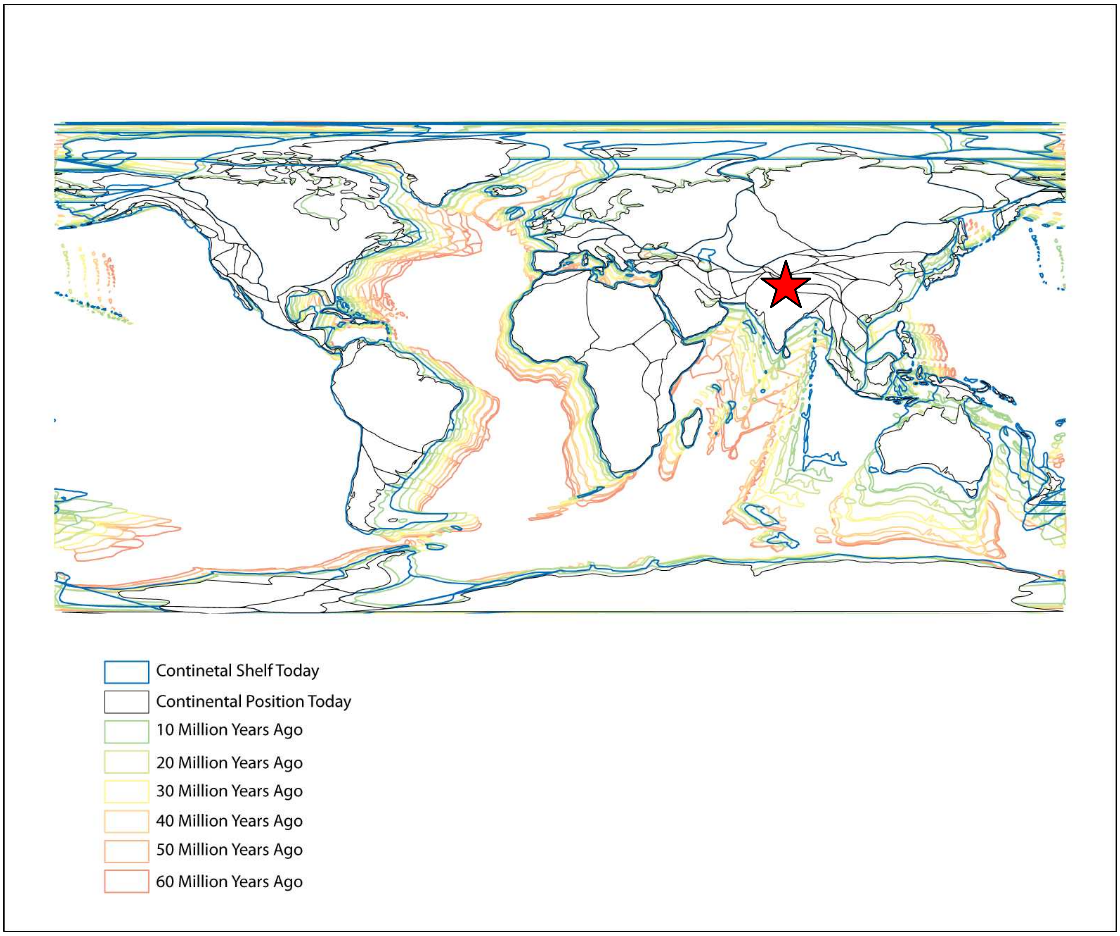


Figure 5.14.The position of Earth's continents changed during the Cenozoic Era. This map shows the positions of the continents over the past 60 million years. Note in particular the rapid movement of India into Asia, a collision that continues to form the highest mountains on the planet—the Himalayas (red star). The separation of Australia and South America from Antarctica may have contributed to global climate cooling and the formation of ice sheets on Antarctica. You can also see that North America has stayed far north of the equator during the Cenozoic, primarily moving west-southwest (Box 5.5). (Paleogeography compiled by Jason Kenworthy using GIS layers from Scotese [2001].)

***Digging Deeper Box 5.7*. The Eocene began with a blast!**

There is a pronounced "spike" on the global climate graph (Figure 5.3) that corresponds to a very rapid warming event 55 million years ago. A blast of greenhouse gas has been implicated in this rapid warming, called the "Paleocene-Eocene Thermal Maximum" or PETM. Along the continental slopes of the world's oceans, cold temperatures and high pressure "freeze" methane—an important greenhouse gas—into water, forming "clathrete" or "methane hydrate." As long as temperatures remain cool enough, that methane is locked up and out of the atmosphere. Fifty-five million years ago, deep sea temperatures increased enough to release the methane very rapidly. Earth's temperature rose as much as 9°F (5°C) in about 10,000 years (Zachos and others, 2008). Scientists are still working to understand the underlying causes of the PETM and how they may or may not be applicable to modern climate change. According to one study, Zachos and others (2008) point out that the amount of greenhouse gasses released during the PETM over a period of thousands of years are comparable to the amounts that could be released by humans over the coming *hundreds* of years.

Chapter 6

Horse fossils in the Cenozoic fossil parks record migration, evolution, and extinction as ecosystems changed.

As the Cenozoic landscape of western North America was evolving and climate was cooling and drying, the communities of plants and animals were also changing. Open ecosystems became more common and grasses more dominant (Chapter 5). The story of change is narrated by more than 10,000 species and millions of specimens of fossil plants, insects, fish, reptiles, birds, and mammals preserved within the Cenozoic fossil parks. Each group of organisms has their own story to tell, with other members of their community playing supporting roles, but the biggest story of the Cenozoic Era is the extraordinary evolution of mammals. Prothero (2006) provides an easy-to-read summary of life during the Cenozoic, particularly the rise of mammals after the extinction of the dinosaurs (Box 1.3). One **family** of mammals may serve as an interpretive thread through the Cenozoic fossil parks—the horse family (Equidae). They are a quintessentially North American animal, with most of their evolution and diversification occurring in what would become the United States. The modern **genus *Equus***[5] (Latin for "horse"), which encompasses horses, zebras, and donkeys, is the only genus in the family today. But the horse family was much more diverse earlier in the Cenozoic, with more than two dozen genera and a few hundred **species** found in the fossil record (Figure 6.1) (MacFadden, 1992). Icons of the American West, modern horses are massive, hoofed **grazers** with a penchant for speed. The earliest equid[6] ancestors, evolving 55 million years ago, were much different—small, dog-sized **browsers** with four toes. All six of the Cenozoic fossil parks preserve horse fossils including the earliest horse ("***Hyracotherium***") and the first horse of the modern genus *Equus*.

The family tree that connects today's horses with those of 55 million years ago is not a straight piece of lumber progressing toward a "better" horse as paleontologists envisioned during the late 1800s (for example, Marsh 1879 [Box 6.1]). This linear interpretation was in line with early evolutionary theory[7]. However, representations of the horse family tree became bushy and increasingly complex

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[5] Bold words are in the glossary. For many of the scientific names, the glossary includes the name's origin (etymology).

[6] Today we differentiate between horses, zebras, and donkeys even though all are species in the genus *Equus*. Likewise, other genera on the horse family tree are not "horses" as we think of them. Technically they should be collectively referred to as "equids." Because this name does not resonate with visitors, it is acceptable to use the term "horses" in a broad sense to refer to all members of the horse family. A brief mention of this discrepancy may clear up any confusion.

[7] Charles Darwin and his supporters (particularly Thomas Henry Huxley) considered the horse one of the best illustrations of gradual evolution by natural selection in the decades following Darwin's *On the Origin of Species* (1859). Huxley visited North America and was particularly enthralled with the fossil record of horses from the American West, including those that Yale's prolific paleontologist O.C. Marsh studied at what is now John Day Fossil Beds NM and Badlands NP. Drake (1978) details the

during the early and middle 1900s, and continue to be refined today (Gidley, 1906; MacFadden, 1992, 2005; Simpson, 1951; Stirton, 1940). In many cases, ancestral horses lived at the same time as more derived forms—similar to modern humans and Neanderthals living simultaneously—indicated by the overlapping time spans on Figure 6.1.

Because horse family fossils are found in each of the Cenozoic fossil parks, they provide an interpretive link between the six parks and an opportunity to interpret evolutionary changes during a time of landscape and climate changes (Chapters 4 and 5). Every living thing is adapted to a particular range of ecosystem conditions. When ecosystem conditions change outside of this range, populations migrate to more favorable conditions, adapt to the new conditions, or go extinct. The horse family tree includes stories of migration within and from North America, adaptation through experimentation and opportunism (the hallmarks of modern evolutionary theory) and even extinction as only one genus survives today—*Equus* (Box 6.2). Through 55 million years of rising mountains, erupting volcanoes, and a cooling and drying climate, the horse family evolved along with and survived the changing ecosystems of the Cenozoic (Figure 6.2). This chapter summarizes the major branches of the horse family tree preserved in the Cenozoic fossil parks. The chapter concludes with discussion regarding how the family tree changed in response to migration, evolution (particularly in feet, teeth and diet, and overall size), and extinction.

Eocene Epoch: Time of the Earliest Horses (52 to 40 million years ago at Fossil Butte NM and John Day Fossil Beds NM)

The very first horses appeared nearly 55 million years ago on a greenhouse Earth with subtropical forests extending north of what is now Wyoming. The earliest members of the horse family found in the Cenozoic fossil parks are 52 million-year-old specimens of "*Hyracotherium*" from the stream bed, floodplain, and even lake deposits of Fossil Butte NM (Figure 6.3). The classification and early evolution of the horse family is an active field of research. Although early horses are commonly called "*Hyracotherium,*" that name is no longer appropriate for North American horses (Froehlich, 2002), hence the quotation marks around the name. Thus, the first horses are here referred to collectively as "hyracotheres." Their fossils are assigned to a half dozen different genera. For example, other hyracothere specimens from the Fossil Butte NM area may be more correctly identified as *Minippus index* (Froehlich, 2002), although the specimen in Figure 6.3 has not yet been further identified (Arvid Aase, Fossil Butte NM, pers. comm., February 2009). The earliest horses generally lived in subtropical forests—like those of Fossil Butte NM—common to western North America during the Eocene Epoch. But some populations lived in more open ecosystems (Gingerich, 1981). In either place, hyracotheres ate little if any grass, as grass was not a major component of western North

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contributions of Oregon's founding father of geology, Thomas Condon, and horse fossils from the John Day Fossil Beds NM area to Marsh's work.

American ecosystems during the Eocene. Although traditionally viewed as browsers eating leaves, pits and scratches on their teeth suggest the diet of early horses consisted of fruits and nuts—abundant in the greenhouse world of the Eocene (Solounias and Semprebon, 2002).

The earliest horses were equipped with four toes on their fore limbs and three on their hind limbs, all of which touched the ground (Figure 6.4). Instead of a hoof, the feet had fleshy pads like dogs. While not Kentucky Derby contenders, these earliest horses already had some adaptations for speed. Unlike humans, they did not walk with their palms or soles on the ground. Their palms or soles were slightly elevated like a foot in high heels. This is an early adaptation for speed over power (Rose, 1990). MacFadden (1992) suggested a gait similar to that of a modern tapir (a South American and Southeast Asian large browsing mammal with a pig-like shape). The "low crowned" (**brachydont**) teeth of hyracotheres and other early horses such as ***Epihippus, Orohippus,*** and ***Haplohippus*** (part of the Clarno assemblage at John Day Fossil Beds NM) were not true molars and had "peaks." These teeth are in distinct contrast to the complex ridges found on the "high-crowned" (very **hypsodont**) horse teeth from Hagerman Fossil Beds NM (Figures 6.5 and 6.6). Hyracotheres would have had little trouble hiding in the understory of sub- or nearly-tropical forests as they ranged in size from house cat to border collie (Figure 6.7) (MacFadden, 1986). Although much younger (44-40 million years old), the horses *Orohippus*, *Epihippus*, and *Haplohippus* at John Day Fossil Beds NM were similar to the hyracotheres. Not much is known about these three horse genera. They were not as common as hyracotheres, and very little of their post-cranial (everything except the skull and teeth) skeletons have been discovered (MacFadden, 1998). The early horses of John Day Fossil Beds NM populated the nearly-tropical forest ecosystems of the Clarno Formation (Hanson, 1996; Manchester, 1994) (Figure 6.2). Global greenhouse conditions during the early Eocene and the positions of the continents made it easy for these earliest horses to migrate across much of North America (fossils have been found in the western and southeastern United States) and into western Europe and southeast Asia. This was a period of global mammal migration—more on that later.

Middle Eocene and Oligocene Epochs: Emergence of the Three-Toed Horses (37 to 24 million years ago at John Day Fossil Beds NM, Badlands NP, and Florissant Fossil Beds NM).

Following the earliest group of horses, the next major branch on the family tree was the emergence of **tridactyl** horses during the middle Eocene about 42 million years ago. Tridactyl (three-toed) horses evolved on a cooling planet during the end of the Eocene. The "pinky" on their forelimbs became **vestigial** so that the horses had three toes on both their front and hind feet (Figure 6.4). ***Mesohippus*** was the first of these tridactyl horses and is the most common horse found in the Cenozoic fossil parks, with discoveries from John Day Fossil Beds NM, Badlands NP, and Florissant Fossil Beds NM. *Mesohippus* fossils are found in the last of the greenhouse ecosystems in the Cenozoic fossil parks, including the forests of the Chadron Formation (Badlands NP) and Florissant Formation (Florissant

Fossil Beds NM) (Figure 6.2). *Mesohippus* and ***Miohippus*** are much better known from icehouse paleoecosystems of the Oligocene such as Turtle Cove woodlands (John Day Fossil Beds NM), and the more open savannahs and steppes of the Brule and Sharps formations (Badlands NP) (Figure 6.2). In fact, the Chadron and Brule formations within and surrounding Badlands NP are among the best places on the planet to study these three-toed horses because of their exceptional preservation (Prothero and Shubin, 1989) and abundance—*Mesohippus* remains make up nearly a quarter of all the fossils discovered in the gallery woodlands of the Brule Formation (Retallack, 1983). *Miohippus* is similar to and sometimes found alongside *Mesohippus* in both John Day Fossil Beds NM and Badlands NP. *Miohippus* tends to be more common in stream-side ecosystems, whereas *Mesohippus* may have been farther ranging (Retallack, 1983). Both are traditionally regarded as browsers (MacFadden, 1992). But, based upon tooth wear patterns, *Mesohippus* may have been dining on some early grass (Solounias and Semprebon, 2002). The tridactyl horses had true molars with a "W"-shaped ridge (Figure 6.5) that may have helped grind increasingly gritty food. *Mesohippus and Miohippus* were about the size of a large collie.

Miocene Epoch: The Golden Age of Horses (24 to 5 million years ago at John Day Fossil Beds NM and Agate Fossil Beds NM).

After 30 million years as four- or three-toed, collie-sized animals, the horse family tree underwent spectacular branching during the Miocene from about 23 to 7 million years ago, followed by a rapid drop in diversity but increase in abundance (Figure 6.1). The Miocene was also the warmest time since the Eocene and marked the great expansion of savannah and grassland ecosystems throughout western North America (Chapter 5). For the first time since "*Hyracotherium*," horses migrated outside of North America to Europe, Asia, and much later, Africa and South America. During the Miocene—and in many cases overlapping in time and space with each other—there were giant horses as well as dwarfs. The first true grass grazers took advantage of increasingly available grass as a food source, while some continued as specialized browsers. Some horses evolved high-crowned teeth while some retained low-crowned teeth. Three-toed horses were still common but the first one-toed hoofed horses appeared later in the Miocene. Two parks preserve horse fossils from many of the Miocene branches: John Day Fossil Beds NM—which preserves at least one fossil horse from each major Miocene branch—and Agate Fossil Beds NM with fossils from two quite different branches.

From about 26 to 19 million years ago, the wooded grasslands and desert shrublands of the "upper John Day Formation" ecosystems were home to two very different horses. ***Kalobatippus*** was a very large, three-toed horse—horses on this branch of the family tree were giants weighing an estimated 880 to 1,300 pounds (400 to 600 kg), the upper end of which is similar to modern domesticated horses (Figure 6.7) (MacFadden, 1986). With low-crowned teeth, *Kalobatippus* is regarded as a very specialized browser (MacFadden, 1998). *Kalobatippus* fossils have also been discovered in the older

Kimberley Member at John Day Fossil Beds NM (Albright and others, 2008). At the complete other end of the size scale—and a different branch of the family tree—was ***Archaeohippus***. This horse was also three-toed and likely a browser, but instead of being a giant, *Archaeohippus* was a dwarf, nearly the same size as the 30 million-years-older hyracotheres (Gould and MacFadden, 2004; MacFadden, 1986).

Although certainly not well-known for its horse fossils, the 19.2 and 23 million-year-old semi-arid ecosystems of Agate Fossil Beds NM were home to *Kalobatippus* horse fossils, like those at John Day Fossil Beds NM. Agate Fossil Beds NM was also home to ***Parahippus***, a horse on a branch of the family tree leading to today's horses (Figure 6.1). *Parahippus* was three-toed, but of medium build (MacFadden, 1986). As a wide variety of horses have been lumped into *Parahippus*, there are a variety of "medium" crowned teeth (**mesodont**) and some of the very first higher-crowned teeth. Historically, *Parahippus* teeth were used to infer a mostly browsing diet, but based upon scratches, pits, and other wear patterns on their teeth, some *Parahippus* species were likely mixed feeders incorporating some grasses into their diets (Solounias and Semprebon, 2002).

The savannahs and open forests of the Mascall Formation ecosystems at John Day Fossil Beds NM were home to a variety of different horses (Figure 6.2). ***Hypohippus*** was a very large, three-toed browser, on the same branch of the family tree as the younger *Kalobatippus*. The dwarf *Aracheohippus* was also present, as were smaller, lower-crowned species of three-toed *Parahippus*. Horses from an historically-important genus, "*Merychippus*" also roamed the Mascall ecosystems. "*Merychippus*" horses are from a large number of different species. Some species are the first horses with high-crowned (hypsodont) teeth, and as such were originally considered the first grazing horses (MacFadden, 1992). However, the genus likely includes species from two branches on the family tree (as shown on Figure 6.1), so its name is in quotation marks (MacFadden, 1998). Although three-toed, "*Merychippus*" species like those preserved in the Mascall paleoecosystems were part of a branch of the horse family tree where the side toes likely only touched the ground while running (Figure 6.4). The Mascall Formation ecosystems existed during the most diverse period in the Equidae history, with at least dozen genera found throughout North America.

The last chapter of Miocene horses in the Cenozoic fossil parks was written by fossils of the Rattlesnake Formation ecosystems within John Day Fossil Beds NM. Advanced, three-toed, high-crowned horses—likely grazers—explored the grassland ecosystems. The side toes on these tridactyl horses, including the larger ***Neohipparion*** and the smaller ***Nannippus***, only touched the ground during running. The Rattlesnake grasslands were also home to the oldest one-toed (monodactyl) grazing horse found in the Cenozoic fossil parks—***Pliohippus***. *Pliohippus* was a large horse with high-crowned teeth and was quite common during the middle Miocene (MacFadden, 1998). The Rattlesnake discoveries were among the last for this genus—and many other grazing forms—as a wave of extinctions pruned the family tree beginning about 10 million years ago.

Pliocene Epoch: Modern Horses Evolve (3.2 million years ago at Hagerman Fossil Beds NM)

The 50-million-year story of horse and ecosystem evolution in the Cenozoic fossil parks culminates at Hagerman Fossil Beds NM. The approximately 3.2 million-year-old Hagerman Horse Quarry, excavated primarily during the 1930s contains a remarkable sample of *Equus simplicidens*, the first member of the modern horse genus (Gazin, 1936; Gidley, 1931). With thousands of bones, including nearly 30 complete skeletons and dozens of skulls, from more than 200 individuals, the horse quarry is interpreted as a mass mortality where large numbers of animals died over a relatively short period of time(McDonald, 1996). Such a mass mortality may have been associated with a prolonged period of drought; the remains were buried shortly thereafter by a flash flood (Richmond and McDonald, 1998; Ruez, 2006). This interpretation is not unlike that for the animals preserved in the bone beds of Agate Fossil Beds NM (Hunt, 1990). As the earliest member of the modern horse genus—its closest modern relative is likely the Grevy's zebra of Kenya and Ethiopia (Skinner, 1972)—the Hagerman Horse would be easily recognizable today. It was a true grazer with high-crowned teeth (Figures 6.5 and 6.6). With a one-toed hoof, it walked on its "tiptoe," much like a ballerina (Figure 6.4). The Hagerman Horse was about the size of a modern Arabian horse and weighed nearly 940 pounds (425 kg) (Figure 6.7) (MacFadden, 1986). *Equus simplicidens* is the state fossil of Idaho, making it an excellent interpretive icon and forming connections with the state fossils of Wyoming and Oregon that together tell a story of changing ecosystems throughout the Cenozoic (Figure 5.10). The Hagerman Horse lived in a temperate, savannah-like ecosystem with some areas of pine woodland and other open, more steppe-like ecosystems (Figure 6.2) (Leopold and Wright, 1985). Although the horse family was much less diverse—no more than five genera existed in North America during the Pliocene—they were very abundant. *Equus simplicidens* in particular was found throughout western North America, northern Mexico, and southwestern Canada (Paleobiology Database, http://paleodb.org, accessed February 13, 2010).

Pleistocene and Holocene Epochs: Equid Extinction and Epilogue

The story of the Equidae does not end at Hagerman! As you may remember from your history textbooks, Spanish colonists "introduced" horses to the New World during the 1500s. What happened to all the Cenozoic horses that evolved and diversified here in North America? After surviving for more than 55 million years and adapting to a host of different ecosystems, the horse went extinct in North America about 12,000 to 10,000 years ago as the last ice sheets of the most recent ice age retreated from North America (Chapter 7). In fact most large mammals (camels, mammoths, mastodons, lions, saber-toothed cats, etc.) went extinct in North America at that time. Some, for example the mammoths, mastodons, and saber-toothed cats, went extinct globally. These extinctions were likely triggered by a number of causes, including changing climate and the emergence of a new predator—modern humans. Populations of the horse *Equus* migrated (*travelled*) to Europe and Asia during the late Pliocene, where they survived the Pleistocene ice ages. Just a few centuries ago, humans returned horses to their ancestral Eocene homeland here in North America!

Migration, evolution, and extinction widened the horse family tree, added new branches, and pruned back others.

The family tree and history of any group of animals or plants results from migration (*travel*), adaptation (*evolution*) and extinction (*death*) as a result of changing ecosystems—landforms (*terrain*), climate (*environment*), and life (*demographics*) (Box 6.2). Ecosystem changes may result from the removal or formation of a physical barrier (mountain range, or ocean basin), or a change in climate, or competition from other living things. Migration, the movement of populations to different areas or even continents, can expand, or contract the areas where animals or plants are found. Interpreters can think of this as the increase in area "shaded" by the family tree. Evolution, changes in populations of living things over time, adds new genera and species (and even higher taxonomic ranks). This can be thought of as the family tree adding branches as it grows from its roots. Extinction, the death and permanent disappearance of a population of living things (not necessarily all at the same time), removes lineages. This can be thought of as "pruning" the family tree. All of the horses we've met in the previous sections of this chapter are from the major branches of the horse family tree (Figure 6.1) and thus tell stories of migration, adaptation, and extinction as their Cenozoic ecosystems changed (Chapters 4 and 5). Not every Cenozoic fossil park has a set of Cenozoic-spanning horse fossils that can be used by interpreters. The horse fossil kit from John Day Fossil Beds NM is one source of tangible horse fossils for interpretive use (Box 6.3; Figure 6.8).

<u>Migration: Expansion or contraction of the family tree</u>

Migration (*travel*) is one manner in which populations can respond to changing ecosystems. Migrations can result from the expansion of habitable ecosystems (populations cover more of the planet) or their contraction (populations cover less of the planet). Humans are quite adept at migrating, although perhaps more often in the United States as a matter of preference than survival. You may know people like my mom's aunt and uncle who "migrate" to Florida to avoid the onset of the cold and snowy winter. In the horse family, major migrations occurred during warm climates of the Eocene and the Miocene.

The Eocene's warm climate—with ample vegetation and no ice sheets in the way—and favorable arrangement of the continents facilitated migrations between Asia, Europe, and North America for numerous groups of animals, mammals in particular (Prothero, 2006). Two migration routes appeared to be used: the Bering Strait between what is now Alaska and Russia connected North America and Asia, while a northeastern route through the North Atlantic via what is now Greenland and northern Scandinavia connected North America and Europe (Figure 6.9). Of great importance to the horse story, is that the odd-toed **perissodactyls** first migrated to North America about 55 million years ago. The first perissodactyls may have been European or Asian, travelling over the North Atlantic or Bering Land Bridge, respectively (Woodburne, 2004a). This group of ancestral perissodactyls would then give rise to the earliest horses in western North America. During the early Eocene, the hyracotheres then migrated back to Eurasia as evidenced by discoveries in western Europe and China (Paleobiology Database, http://paleodb.org, accessed February 6, 2010) (Figure 6.1 and 6.9). But they did not last long in Eurasia and were extinct by about 50 million years ago. When icehouse climates began during the Oligocene, there was minimal migration and the horse family was restricted to North America (Figure 6.9). Note the narrow width of the horse family tree during the Oligocene on Figure 6.1.

The next major migration of horses outside of North America came during the early Miocene, beginning about 23 million years ago—not coincidentally during the next interval of globally-warm climates (Figure 5.3). The Bering Strait was a major migration route as mammal groups again moved from Asia into North America and vice versa. However, by this time the North Atlantic had spread too wide for migration between North America and Europe (Figure 6.9). Large, three-toed browsing horses from the same branch of the family tree as *Kalobatippus* and *Hypohippus* migrated into Asia. Their fossils are found in western Europe and China. This was the first time since the Eocene that horses travelled beyond North America. Immigrants to North America from Asia during this time of massive global migrations are found in other Cenozoic fossil parks and particularly evident at Agate Fossil Beds NM. The two most common animals at the park, the rhinoceros *Menoceros* and chalicothere *Moropus*, as well as the bear dogs *Ysingria* and *Daphoenodon* were all recent immigrants from Asia (Woodburne, 2004a). The fearsome entelodont *Daeodon* was a soon-to-be extinct North American native.

Migrations also took place within North America during the Miocene, and were influenced by the cooling and drying climate (and accompanying expansion of savannahs and grasslands) during the later Miocene. For example, as savannahs and grasslands spread throughout the plains and western North America, warm temperate forests remained in the Gulf Coast and Southeast—my mom's aunt and uncle travel there today for the same reason! These areas became "refuges" for some species of *Pseudhipparion* and *Nannippus* and other horses more adapted to browsing or selective grazing after they became extinct in the plains and southwest (Maguire and Stigall, 2008).

<u>Adaptation and evolution: Adding branches to the family tree.</u>

Horses changed (*evolved*) in many ways from those first hyracotheres to the modern genus *Equus*. In this section we will focus on three major changes through time—horse feet, teeth and diet, and overall body size. These are readily identifiable in the fossil record and by visitors. When discussing evolution and change through time, remember that while the early horses may seem maladjusted and antiquated compared to today's horses, they were well adapted for their particular time and place (Box 6.1). Early studies of fossil horses (and some exhibits today) suggested primarily linear changes during the horse family evolution where larger running horses with less toes, eating more grass replaced smaller, slower multi-toed horses that ate less grass. This section will illustrate how horse evolution and the family tree went through many non-linear branches—most of them added during the Miocene (MacFadden, 2005).

Hooves are an easily recognized characteristic of modern horses. But the one-toed hoof is a relatively new development in the horse family. The first horses had four toes on their front feet. These correspond to human index, middle, ring, and pinky fingers. Interpreters can illustrate changes in the forelimb ("hand") of horses using their own or volunteers' hands, as shown in Figure 6.4. Just as in humans, the middle "finger" of horses was longest. In the hyracotheres, this middle finger supported most of the weight but all four fingers touched the ground. The foot however was not flat on the ground, as they held their heels and "wrists" off the ground (MacFadden, 1992). *Mesohippus* marked the first of the true tridactyl (three-toed) horses (the pinky became vestigial) where all three toes touched the ground (MacFadden, 1998). During the Miocene, the very bushy family tree contained branches with different feet styles. Some branches continued as advanced tridactyl horses (such as *Hypohippus*, *Kalobatippus*) (MacFadden, 1998). Others branches became more monodactyl ("one-fingered") with their middle "finger" increasing in size to support more of the weight of the horse. Their side fingers perhaps only touched the ground while running (such as some species of "*Merychippus*" or *Neohipparion*). Like training wheels on a bike that do not always touch the ground, the side toes may have imparted stability while running or on muddy ground (MacFadden, 1992). These horses were the first to have true hooves—made of the same material as human fingernails. The branch of the Equid family tree that became fully monodactyl around 7 million years ago includes younger species of *Pliohippus* and the modern *Equus*. By this time, these hoofed horses were standing on their tip-toes, much like a ballerina. This adaptation also favors speed—human sprinters run on their toes rather than flat-footed. The "splint" bones of modern horses found way up their legs, near their "wrist" (Figure 6.4) are all the evidence that remain of the extra "fingers" found on horse feet for more than 50 million years!

The old adage advises: "you are what you eat." Indeed, for fossil animals, teeth hold many clues to ancient meals. Being so durable, teeth are readily preserved in the fossil record, and for many mammal groups are the most common body fossil discovered. Their size and shape can suggest an animal's diet as do scratches, pits, and other wear patterns (Solounias and Semprebon, 2002). Interpreters commonly do this for modern animals, comparing the sharp incisors of a carnivorous predator to the flatter, grinding teeth of an herbivorous grazer. Modern horse teeth are high-crowned for durability and have many ridges to help process their primary food source: grass. If you have ever put a piece of grass in your mouth, you know it is quite "prickly." The prickly-ness of grass comes from its internal "skeleton" of distinctively shaped pieces of silica (the same element found in the mineral quartz, glass, and most beach sand) called **phytoliths**. Eating grass your whole life would be like chewing on sandpaper every day. It would be nice to have teeth that were up to the challenge! As we've seen above, not all horse teeth were high-crowned, early horses had low-crowned teeth (so do you!) with "peaks" on their molars, forming a serrated edge (Figure 6.6). A serrated edge, like that on scissors, is good for slicing leaves and cutting fruits and nuts but not good for grinding back and forth on abrasive grasses. *Mesohippus* and *Miohippus* had a "W" shaped ridge on their molars that may have facilitated chewing some grasses (Solounias and Semprebon, 2002) (Figure 6.5).

For many years paleontologists noted that horses teeth grew taller and grassland ecosystems expanded during the Miocene in North America. This was thought to be a classic case of coevolution, as the horse evolved many adaptations, including tooth size, to take advantage of this increasingly available food source. Continued research using dating techniques with higher resolution (like the argon-argon method in Chapter 3) has shown that the appearance of high-crowned horse teeth ("*Merychippus*" was the first) occurred as much as 4 million years after the appearance of grasses, based on fossil phytoliths (Stromberg, 2006). Likewise, Retallack (1983) interpreted early grasslands and savannahs 30 million years ago at Badlands NP during the time of low-crowned *Mesohippus* and *Miohippus*. The high-crowned tooth is now thought to be more an adaptation for increased durability than a reliable indicator of diet and some higher-crowned horse may have been browsers based on wear patterns (Janis, 2008; Solounias and Semprebon, 2002). Therefore it appears horses did not make an instantaneous switch to a primarily grassy diet. Regardless of the timing, by the end of the Miocene horses were primarily grazers and have been that way ever since. Their rapid evolution during the early and middle Miocene may have been fueled by early savannahs and primitive, short grasslands. When modern, tall grasslands took hold about 7 million years ago horse diversity plummeted through extinction. But, the horse family was not down for the count, as the number of individual horses became very abundant. Through migration, horses populated every continent save for ice-enshrouded Antarctica and geographically-isolated Australia by the Pleistocene about 2 million years ago. Modern horses are synonymous with grasslands and the open ecosystems of the American West. As humans we can relate to a dependence on grasses—most of us eat something from the grass family nearly every day (Box 6.4).

The overall size of the horse increased dramatically over time. MacFadden (1986) used various tooth and skull size measurements to estimate body mass of horses through time (Figure 6.7). While the body mass estimates for hyracotheres of about 55 to 66 pounds (25 to 30 kg) are larger than what would be expected for an animal with dog- and cat-sized skeletons, an overall picture of the diversity of body masses emerged. Until about 25 million years ago, horses remained "dog-sized," not exceeding 110 pounds (50 kg). As alluded to in the Miocene section above, horses then attained a wide variety of body sizes at the same time. Some branches like *Hypohippus* and *Kalobatippus* became giants very early on, attaining body sizes between 550 and 880 pounds (250 and 400 kg) by 17 million years ago (Figure 6.7). Others like *Archaeohippus* went the other direction as dwarfs weighing less than 110 pounds (50 kg) 13 million years ago. More recently, horses tended to be larger as the Pliocene horses nearly all exceeded 770 pounds (350 kg). Today horses weigh in at more than 1,100 pounds (500 kg).

As this chapter has shown through the life and times of Mr. TED (Box 6.2), there are many drivers to evolution including external factors such as terrain, evolution, and demographics as well as internal biological factors. Variation in terrain and tectonic activity can fuel evolution by forming varied habitats which in turn challenge the organisms living there in different ways (Kohn and Fremd, 2007). Climate change affects the type of vegetation (food) that grows in an area, which can spur evolution and extinction. Other living things have a profound effect as well, as competitors and predators change, adapt, or migrate. These external factors appear to influence mammal evolution on longer timescales (millions or tens of millions of years) while internal biology and physiology of the organisms affects evolution and adaptation on shorter time scales (Barnosky, 2001).

<u>Extinction: Pruning the family tree</u>

Extinction (*death*) is an important part of the horse story, as it is with every other living thing on the planet. All of the horse species found in the Cenozoic fossil parks are extinct, as are all but one of the horse genera (*Equus*). Extinction is a normal part of the history of life on Earth and an integral component of modern biology and evolutionary theory. Mass extinctions—where many different lineages of living things go extinct at the same time (geologically-speaking)—are a dramatic part of Earth's history and coincide with major alterations in many different lineages or ecosystems around the world. Most visitors are familiar with the large mass extinction 65.5 million years ago at the end of the Cretaceous Period that marked the end of the Mesozoic Era (the Age of Dinosaurs) and the beginning of the Cenozoic Era (the Age of Mammals) (The "K-T Boundary," Box 1.3).

The gray bars on Figure 6.1 show the approximate span of time that each of the different genera existed. Where a gray bar ends marks the extinction of that particular genus. Extinctions pruned the family tree of the hyracotheres and other early horses by the end of the Eocene. Interestingly, the major climatic shift from greenhouse to icehouse did *not* coincide with horse family (or most other mammal families) extinction in North America. In North America, a wave of mammal extinctions, and the first appearance of the three-toed horse *Mesohippus,* occurred about 40 million years ago (Prothero, 2006; Woodburne, 2004a).

Although the Miocene was a time of great expansion of the horse family tree—nearly 20 different genera existing in North America at various times during the Miocene in North America—from about 11 to 5 million years ago, extinctions greatly pruned back the tree. Horse diversity peaked at about 14 and 7 million years ago, when many different branches of the family tree coexisted in North America (Figure 6.1) (Hulbert, 1993; MacFadden, 1992, 2005). Between about 11 and 9 million years ago, this diversity started to wane. Horses like the specialized three-toed browsers *Kalobatippus* and *Hypohippus* went extinct as did other horses without high-crowned teeth. Horse diversity began a rapid decline at around 7 million years ago. By 3 million years ago, horse diversity was just one-sixth of its peak at 7 million years ago. The end result of these extinction events was the replacement of a very diverse group of horses characterized by a variety of high-, medium-, and low-crowned teeth lengths, along with browsing, mixed feeding, and early grazing diets with a low diversity but high abundance of horses like *Equus*. These horses of large size, with very high-crowned teeth, and a primarily grass-based diet would be readily recognizable today. Some three-toed (but functionally one-toed) horses like *Nannippus* or *Neohipparion* (John Day Fossil Beds NM) survived, but these would go extinct during the Pleistocene. Their extinctions left just *Equus* to represent the horse family during the late Pleistocene in North America, until it, too, went extinct in North America between 12,000 and 10,000 thousand years ago.

What might have caused the great extinctions of the horse family during the end of the Miocene? One potential cause is the loss of some of the conditions that may have served to spur the rapid adaptation and evolution during the early Miocene. The expansion of more-modern, tall grasslands at the expense of short grass savannahs and grasslands occurred about 7 million years ago (Wang and others, 1994). The decline in diversity of horses thus may have coincided with a decline in habitat diversity as grasslands with their more monotonous vegetation expanded (Maguire and Stigall, 2008).

Integrating the horse story into interpretive opprtunities

As a readily recognizable animal with a long history interwoven between all six parks, the story of the horse family provides a powerful interpretive focus. It is also animates a story set against the backdrop of *terrain* and *environmental* changes during the Cenozoic Era (Chapters 4 and 5). The active landscape of the American West, particularly during the Miocene, provided a variety of ecosystems the horse family exploited and adapted to. Those processes also enabled the preservation of horse fossils (along with thousands of other animals and plants) in the Cenozoic fossil parks. The story of climate change in Chapter 5 is particularly important as it contributed to the expanse of grass-dominated ecosystems. These grasses fueled the rise of modern branches of the horse family.

I found the John Day Fossil Beds NM horse fossil kit (as well as other horse fossil specimens from the other parks) a particularly useful tangible to help present these stories. Standing near a table surrounded by fossils (Figure 6.8) was an effective hook to reel in an audience. This is particularly useful at parks where low or sporadic visitation can stymie scheduled formal programs. Even without access to such fossils, important components of the horse family history can be worked into formal and informal interpretation. I would first establish that the fossils are all of horses, despite their many visible differences. Then I would point out that the fossils are representatives from many different parks, but highlight the one(s) from that particular park, providing a "you are here" orientation. Visitors could then pick up and compare horses found at that park to those representing animals that lived before and after. This provides an opportunity to mention the different ecosystems each horse was part of, and to relate how the story of the horse family is tied to the rise of grasslands. The horse teeth are useful tangibles in this regard. You can ask the visitors, particularly young ones, what the different horses might have been eating. This provides a connection to long term climate change from a greenhouse that supported nearly tropical forests to an icehouse supporting cooler and drier grasslands. This provides a great lead-in to modern climate change and the ability to discuss how we as humans (as well as every other living thing on the planet) will face the options of *travel*, *evolution* and adaptation, and yes, even *death*—just like the horse family did—as our planet warms and ecosystems change (Chapter 7).

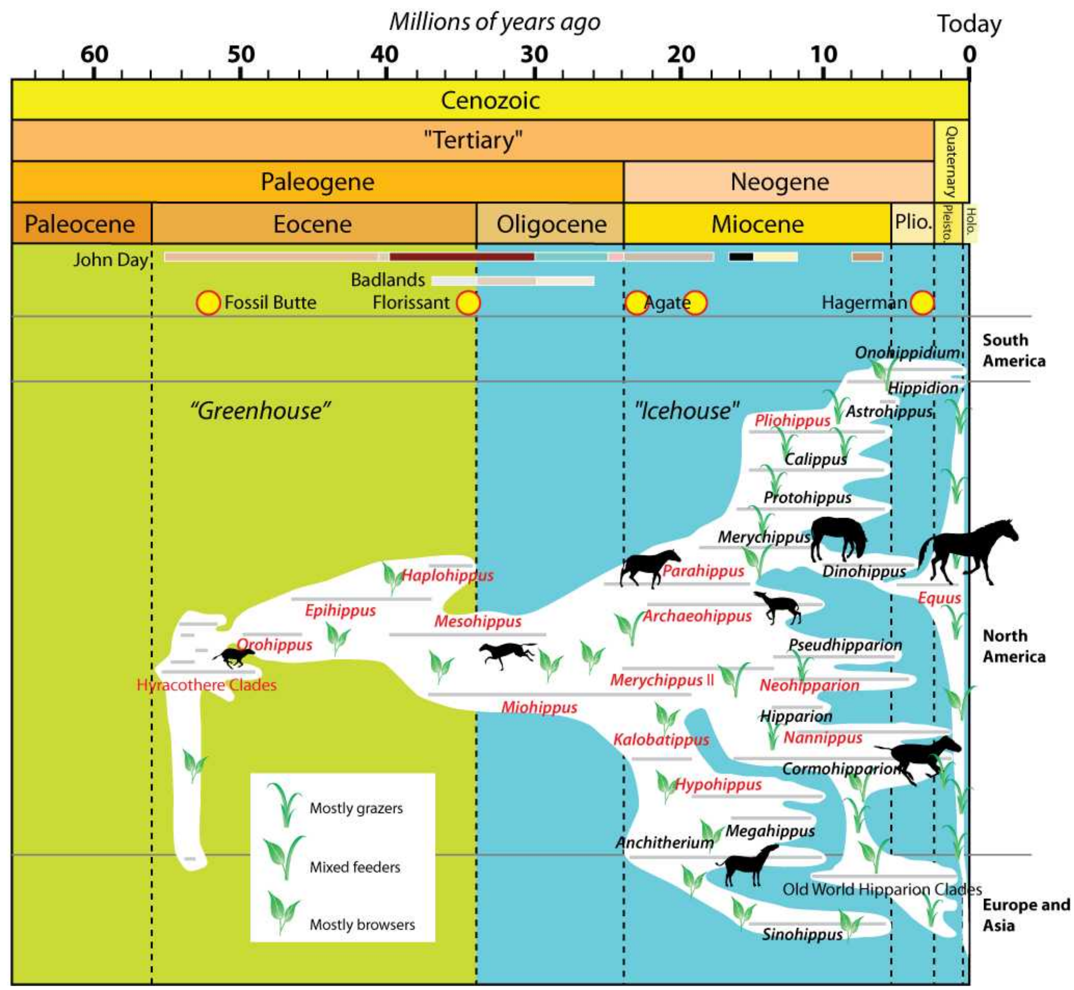

Figure 6.1. The horse family (Equidae) tree resulted from migration, evolution, and extinction during the Cenozoic Era. The gray bars indicate the approximate time spanned by the indicated genera. Genera names in red are represented in one or more of the Cenozoic fossil parks. The leaf icons indicate the inferred diet of horses on each branch of the tree. The Equidae primarily evolved here in North America, migrating to Europe and Asia and South America as indicated. Note the extraordinary "bushiness" of the family tree during the Miocene—the golden age of horses (and many other mammals). Technically, this diagram is called a "phylogeny" because it is based on shared evolved characteristics, but "family tree" is acceptable when talking with visitors. (Horse phylogeny graphic modified from MacFadden [2005], used with permission of the American Association for the Advancement of Science.)

<u>Digging Deeper Box 6.1</u>. Evolution is not "progression."

When interpreting evolution, it is easy to think that today is the pinnacle of progress and that today's organisms are better adapted to their environment than those in the past. Keep in mind that just like one particular ecosystem of the Cenozoic fossil parks, today is just one slice in time. For example, the hyracotheres could be viewed as an ill-adapted small, slow and clumsy animals compared to today's horses. However those early horses were well-adapted for the subtropical environments of the early Eocene. Modern horses (and humans) would fare less well during the climatic conditions of the Eocene, an important note to make in light of climate change models that suggest increased warming in centuries to come.

As paleobotanist Harry MacGinitie (who studied fossil plants from many of the Cenozoic fossil parks) said in a 1979 interview at Florissant Fossil Beds NM, and quoted by Meyer 2003, "*We get all tangled up with the present. The present is just a little flick in time between the past and the future. Things keep going on and on. We are just in this particular little time interval, and it seems so important to us.*"

Paleontologist Stephen Jay Gould, in his essay "Pleasant Dreams," published in *An Urchin in the Storm* (W.W. Norton and Co., 1987) put it another way, "*It seems the height of antiquated hubris to claim that the universe carried on as it did for billions of years in order to form a comfortable abode for us. Chance and historical contingency give the world of life most of its glory and fascination. I sit here happy to be alive and sure that some reason must exist for 'why me?' Or the earth might have been totally covered with water, and an octopus might now be telling its children why the eight-legged God of all things had made such a perfect world for cephalopods. Sure we fit. We wouldn't be here if we didn't. But the world wasn't made for us and it will endure without us.*"

<u>Digging Deeper Box 6.2</u>. "Mr. TED" tells the story of the horse family.

While the popular TV character "Mr. Ed" may be a generic moniker for modern horses, Cenozoic fossil horses can be referred to collectively as "Mr. TED." The choice of "TED" not only provides a name but a potentially helpful mnemonic for the components of a paleoecosystem that serve as the drivers of evolution: *Terrain* (landscape), *Environment* (climate), and *Demographics* (characteristics and composition of the living things in a community—you'll hear this word a lot associated with the 2010 census). Because it encompasses communities of organisms, *demographics* also includes interpretive intangibles such as nourishment, safety, and family. As the tangible ecosystem components change over time, groups of organisms react through another "TED" that closely parallels interpretive universal concepts: *Travel* (move), *Evolution* (adapting to the new terrain, environment, or demographics), or *Death* (extinction).

While Mr. TED may not be able to talk as well as Mr. Ed, equid fossils have a spectacular story to tell. The widely-branching family history (Figure 6.1) of the Equidae is a response to changes in *Terrain*, *Environment*, and *Demographics* as different genera *Travelled*, *Evolved*, and *Died*.

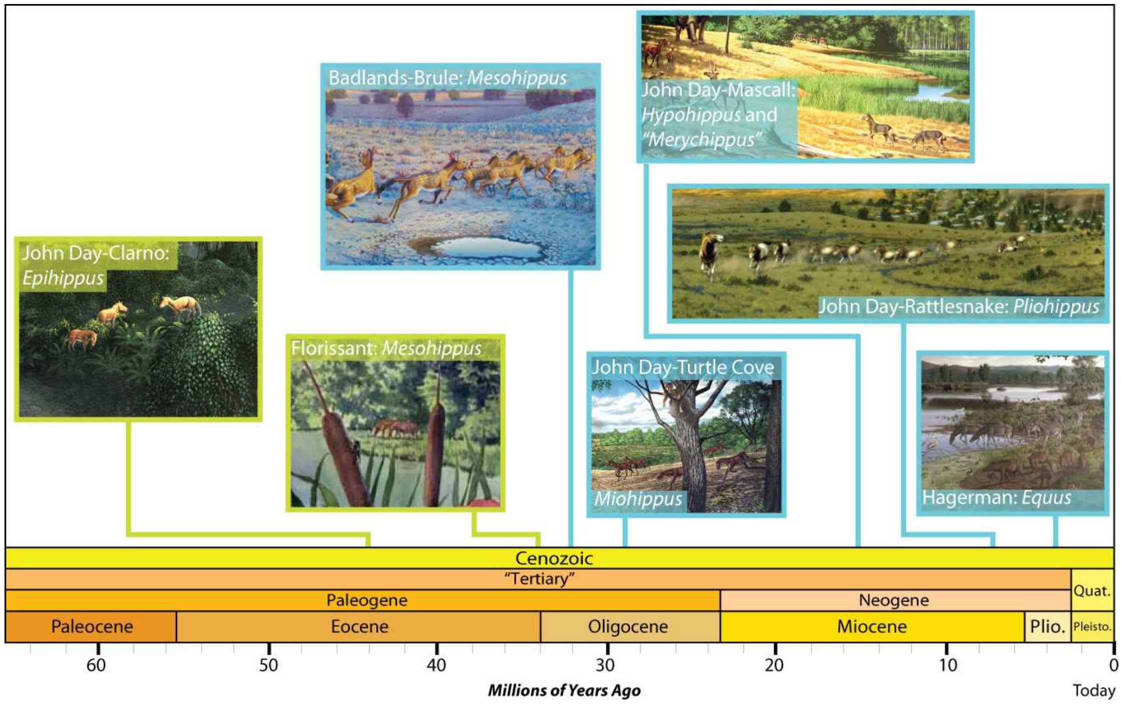

Figure 6.2. Changes in horses and ecosystems are evident in the Cenozoic fossil parks. These "zoom-ins" on Cenozoic fossil park murals show the variety of a sample of Cenozoic horses and interpretations of the ecosystems they lived in. Green lines represent greenhouse ecosystems, while blue lines represent icehouse ecosystems. Equid ecosystems have encompassed nearly tropical forests (e.g., Clarno and Florissant), savannahs and woodlands (e.g., Brule), temperate woodlands (e.g., Turtle Cove), open savannahs and grasslands (e.g., Mascall), semi-arid grasslands (e.g., Rattlesnake), and temperate lake- and stream-side (e.g., Hagerman). Plio. = Pliocene Epoch; Quat. = Quaternary Period; Pleisto. = Pleistocene Epoch (John Day murals by Larry Felder [Clarno] and Roger Witter [all others] for NPS; photographed by Will Landon for NPS. Florissant mural: NPS image. Badlands mural courtesy Badlands Natural History Association. Hagerman mural by Jay Matternes, copyright by the Smithsonian Institution. Used with permission.)

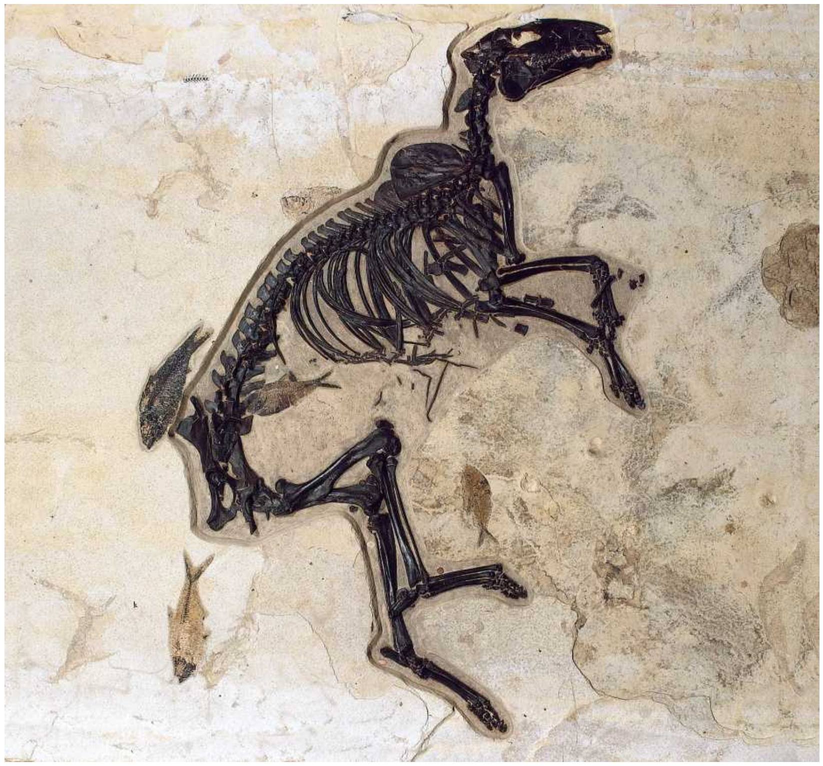

Figure 6.3. This 52 million-year-old "*Hyracotherium*" was discovered in subtropical lake beds of the Green River Formation (note fish fossils!) just outside of Fossil Butte NM in 2003. Early equids were not aquatic—this one apparently fell into the lake or was washed in from the adjacent river floodplains (Wasatch Formation). At approximately 52 million years old, this extraordinarily well-preserved *"Hyracotherium"* represents the oldest horse-family fossil found in the Cenozoic fossil parks. The skeleton is approximately 2 feet (61 cm) long nose to tail, or about the size of a border collie. Other specimens of *"Hyracotherium"* may have been as small as a house cat (MacFadden 2005). (National Park Service photo courtesy Arvid Aase [Fossil Butte NM]).

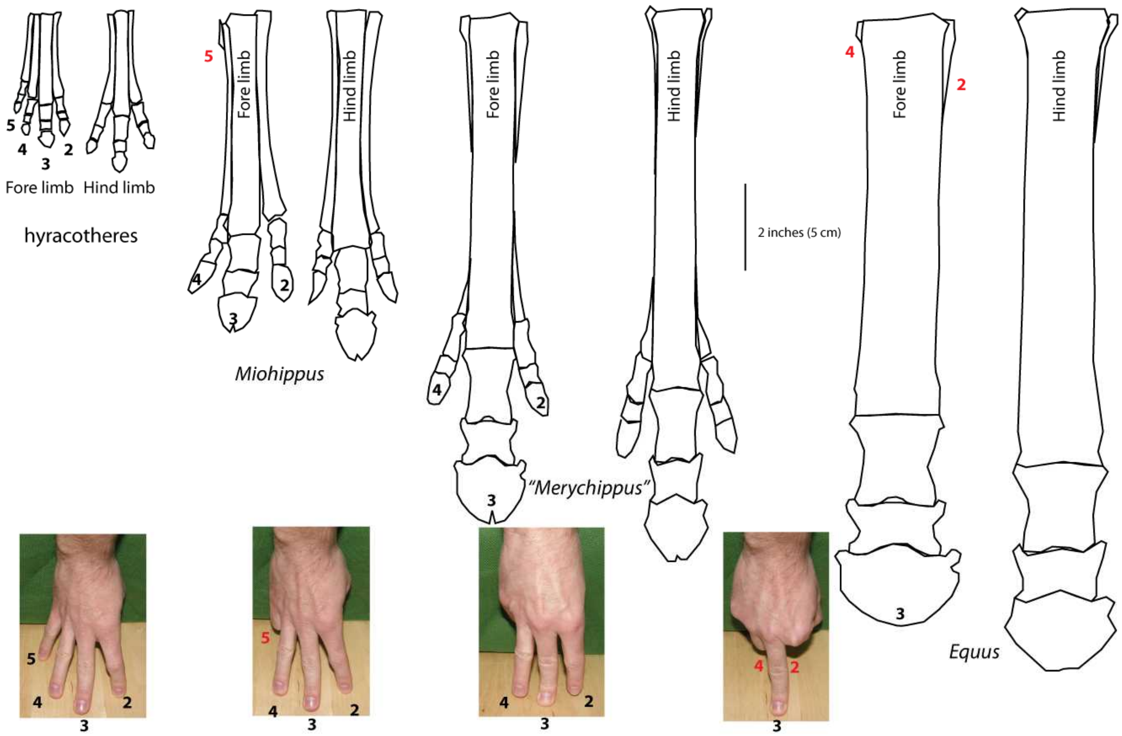

Figure 6.4. Human hands can be used to illustrate changes in horses' hands and feet. Hyracothere "hands" had four digits touching the ground, corresponding to the human index finger (2), middle finger (3), ring finger (4), and pinky (5), with their heel slightly elevated off the ground. Tridactyl horses such as *Miohippus* had three digits touching the ground with a vestigial "pinky." During the Miocene, horses had a variety of foot-types, some species of "*Merychippus*" were three-toed but toes 2 and 4 may have only touched the ground during running. By the Pliocene, *Equus* was one-toed with a prominent hoof and vestigial toes 2 and 4 (these are now the "splint" bones on the back of horses' legs). *Equus* walked up on its tip-toes much like a ballerina. As shown in the illustrations, interpreters can use their hands (or those of visitors) to illustrate these changes. Incrementally increase the angle of your palm off the ground to simulate horses increasingly elevating their stance onto their toes (beware of unintended intangible meanings with the monodactyl gesture for *Equus*!). Black numbers indicate digits touching the ground, red numbers are vestigial. The top of the skeletal sketches begin at the horses' "wrists." (Photographs by Jason Kenworthy; sketches redrawn after Matthew [1926].)

Figure 6.5. The chewing-surface shape of horses changed dramatically over time, as shown from oldest (*Orohippus*) to youngest (*Equus*). A) Early horses like *Orohippus* had distinct "peaks" on their molars (white arrows). These teeth, typical of broswers, were used for snipping leaves and chewing fruit. Fittingly, the horse's name *Orohippus* is derived from the Greek word for mountain, referring to the peaks of the teeth. (Photo by Jason Kenworthy of John Day Fossil Beds NM horse kit replica of UCMP 66799). B) These *Miohippus* teeth still have a "peak"-like profile when viewed from the side. But, as shown in this "top view" *Miohippus* has a zig-zag ridge along the outer (cheek) surface of the teeth (white lines). This surface may have helped *Miohippus* (and *Mesohippus*) process some soft grass in their diet. (Photo by Jason Kenworthy of John Day Fossil Beds NM specimen JODA 8578). C) Typical of grazing teeth, *Equus* teeth are much flatter on top, with complex ridges and grooves (arrows) for grinding grass. These are from *Equus simplicidens*, the "Hagerman Horse." (NPS photo by Phil Gensler [Hagerman Fossil Beds NM] of specimen HAFO 2214.)

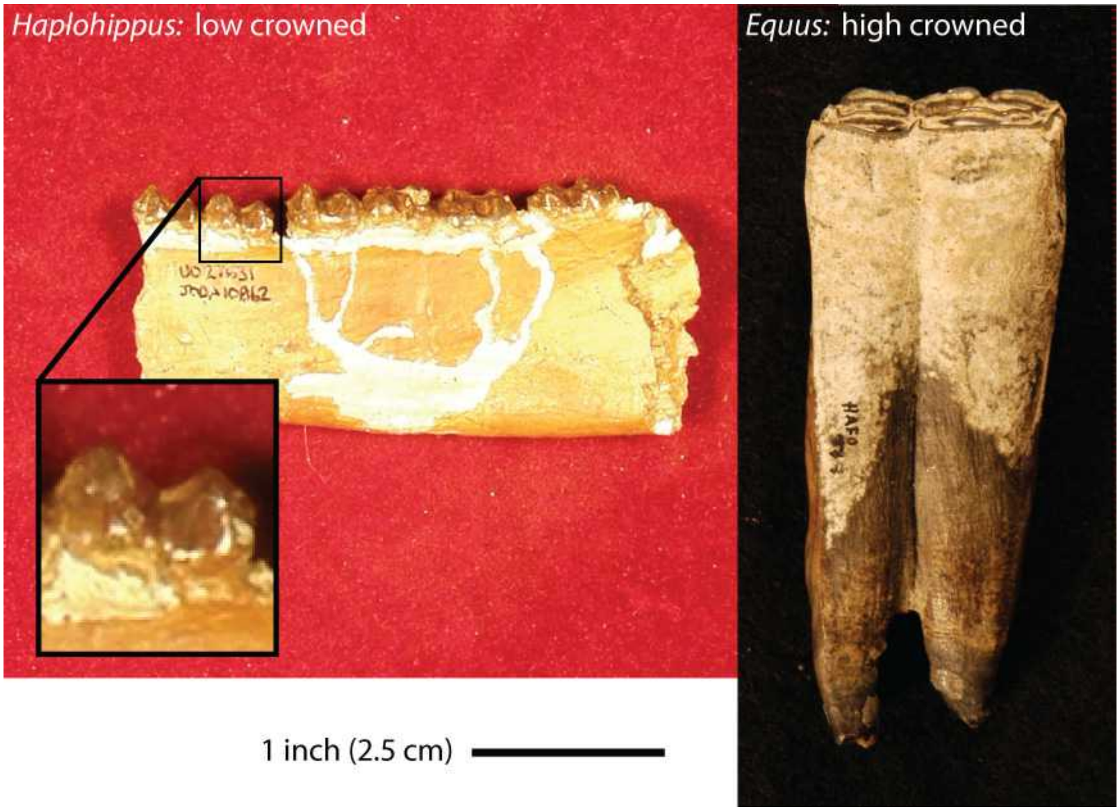

Figure 6.6. Not only did the surface of horse teeth change through time (Figure 6.5), but so did their length. Early horses, like *Haplohippus* had low crowned, or brachydont teeth, where the tooth is not much longer than it is wide. The "zoom-in" shows the profile of the peaks of early horse teeth. These teeth are characteristic of browsers. Humans also have **brachydont** teeth. Contrast these small brachydont teeth with the comparatively enormous high crowned (**hypsodont**) teeth of *Equus* where the tooth is much longer than it is wide. You can also notice the relatively flat top of the *Equus* tooth—a good surface for grinding tough-to-eat grass. The length of the teeth is thought to reflect increased durability, and may not always be a good indicator of dietary preferences. The dark area of the lower *Equus* tooth represents the approximate gum line. These photos are at the same scale. (*Haplohippus texanus* photo by Jason Kenworthy of specimen JODA 10862; *Equus simplicidens* photo by Phil Gensler [Hagerman Fossil Beds NM] of specimen HAFO 777.)

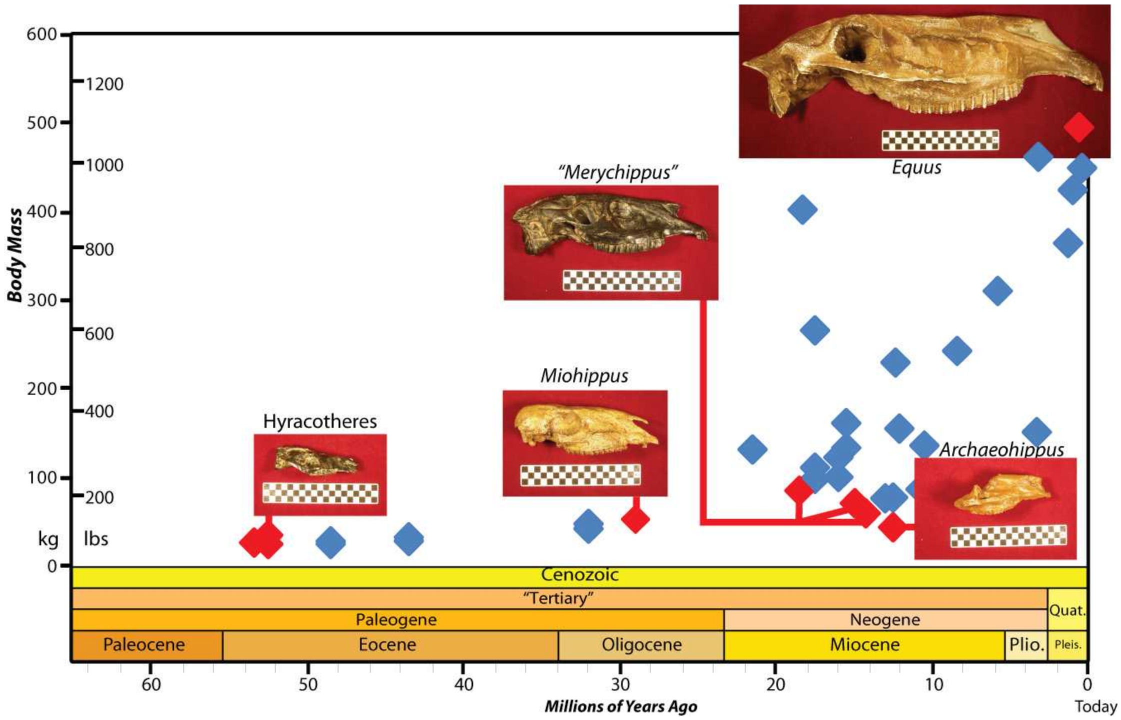

Figure 6.7. Horse body size changed over time. As shown on the graph above, horses were quite small for most of their history. Only starting about 20 million years ago did horses really increase in body size, some quite rapidly! Others stayed small, and some even became dwarfs (like *Archaeohippus*). A selection of skulls is included, shown at the same scale (the checkered scale bar is 7.5 inches, or 19 cm, long). (Skull photos by Jason Kenworthy of John Day Fossil Beds NM horse kit fossil replicas of specimens AMNH 4832, JODA 1086, FAM 60300, AMNH 8174, and LACM 1863. Body size data from MacFadden [1986], with ages updated based upon timescales in Woodburne [2004b] and the collection records of the various horse genera catalogued as part of the Paleobiology Database [http://paleodb.org; accessed April 22, 2009].)

Figure 6.8. Touchable horse fossils + smiling, knowledgeable ranger = interpretive opportunity! At Florissant Fossil Beds NM (one home of *Mesohippus*), the author stands with the travelling horse kit from John Day Fossil Beds NM. The kit contains plastic replicas (exact copies) of fossil horse skulls and teeth, including genera from all the major branches of the horse family tree, making it applicable to other Cenozoic fossil parks (Box 6.3). Utilizing horse fossils from before and after those at your park, help put your park's fossils in chronological and evolutionary context. Note in this photo differences in sizes between the various horse skulls arranged chronologically with youngest—*Equus*—on the left and the oldest horse from John Day Fossil Beds NM—*Orohippus*—on the far right. The large skull in the middle is from the specialized browsing "giant" *Kalobatippus* (Photo by Jason Kenworthy.)

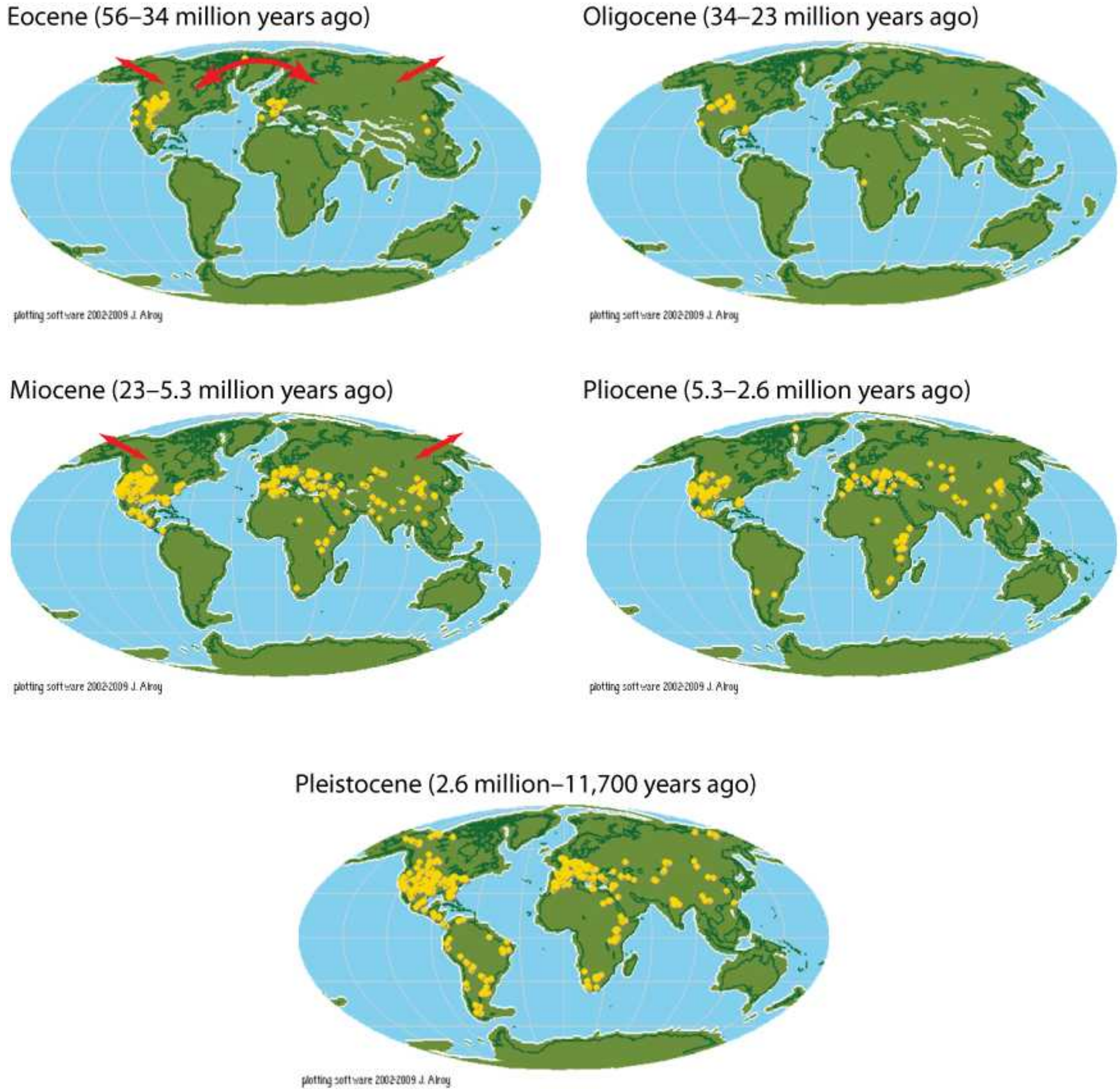

Figure 6.9. Migrations expanded and contracted the horse family tree. The yellow dots show where horse family fossils have been found, representing the Eocene, Oligocene, Miocene, Pliocene, and Pleistocene epochs. During the warm Eocene and early Miocene, horses migrated from North America to Eurasia (red arrows). During the Eocene, horses likely travelled both across the Bering land bridge (connecting Asia and Alaska) and across the North Atlantic (from Canada to Scandinavia via Greenland). By the Miocene, the Bering land bridge was the only connection between the North American and Eurasian continents. During the Oligocene, horse fossils are only found in North America (the dot in Africa is a tentative identification). During the Pliocene, horse fossils were found on every continent except Australia and Antarctica. During the Pleistocene, horses lacked the diversity of the Miocene, but were fantastically abundant and found throughout the world. (Distribution data and paleogeographic maps downloaded from the Paleobiology Database utilizing Equidae records for each time period; http://paleodb.org, accessed February 16, 2010.)

***Digging Deeper Box 6.3*. BYO Horse Fossils**

Although every Cenozoic fossil park preserves horse fossils, not all have such fossils, or reproductions available for use by interpreters. So you may want to "bring your own." The horse fossil travelling trunk from John Day Fossil Beds NM contains life-sized reproductions of a variety of horse skulls and teeth through time (many of the same genera are found at other Cenozoic fossil parks). During my travels to other Cenozoic fossil parks, I borrowed one of these kits, providing a host of touchable tangibles to share with visitors. Having them all laid out on a table (augmented by other fossils from the park) encouraged interpretive opportunities to discuss horse evolution and changing ecosystems during the Cenozoic (Figure 6.8). The kit also contains a variety of classroom curriculum-based educational activities that can be adapted for use in interpretive settings. Contact John Day Fossil Beds NM for more information and availability.

***Digging Deeper Box 6.4*. Grasses fuel humans, too.**

It would be difficult to overstate the importance of the grass family to modern ecology or human economy. For example, Crepet and Feldman (1991) stated the grass family is the "single most important family to the economy of mankind." Indeed, the history of humans has been intimately tied to the domestication of grasses. According to statistics compiled by the Food and Agriculture Organization (2009), more than 46% of the world's total caloric intake comes from cereals which include the grasses rice, wheat, maize (corn), *Sorghum*, barley, millets, oats, and rye. Cereals account for the largest single fraction of agricultural production—just under 2.5 billion tons (that's nearly 5 *billion* pounds!)—about 35% of the world total. Humans are fueled by grasses!

Interpreters can illustrate this concept by asking visitors what they had for breakfast. In most cases, at least some part of the meal can be tied back to grasses (cereals, breads, pastries, granola) or to animals (cows, pigs) that grazed on grass or fodder. The evolutionary story of the horse—and indeed other grazing animals—was increasingly fueled by the rise of grassland ecosystems during the Miocene. The appearance of modern grassland ecosystems by about 7 million years ago led to a decline in horse diversity but an increase in abundance and distribution.

Chapter 7

After the Cenozoic fossil parks, ice advanced and retreated on a cold Earth—Earth is now warming

Our journey through the paleoecosystems of the Cenozoic fossil parks has taken us from 52 million-year-old subtropical forests at Fossil Butte NM; to 34 million-year-old warm temperate forests of Florissant Fossil Beds NM; to 29 million-year-old savannahs at Badlands NP; to 19 million-year-old watering holes at Agate Fossil Beds NM; to 6 million-year-old semi-arid grasslands at John Day Fossil Beds NM; to temperate forested ecosystems at Hagerman Fossil Beds NM just 3 million years ago. During this time, the landscape of the American West changed as the continent grew westward, mountain ranges rose and volcanoes erupted (Chapter 4). Global climate transitioned from a greenhouse to an icehouse (Chapter 5). The horse family was an example of migration, evolution, and extinction—faced by all living things during times of ecosystem change (Chapter 6). The paleoecosystems archived within the Cenozoic fossil parks provide tangible evidence and context for climate and ecosystem change over the long term (Chapter 3, "Were all these fossils found here?"). Because climate and ecosystem changes are the primary interpretive theme of the parks, they are excellent (and necessary!) places to interpret modern climate change.

After the 50 million years of long-term cooling and drying spanned by the Cenozoic fossil parks, Earth's climate was cold enough to support large ice sheets on both the North and the South poles—setting the stage for the Pleistocene "ice ages" (Figure 7.1). This chapter summarizes the major advances and retreats of ice sheets from both poles during the ice ages on a cold Earth beginning about 2 million years ago. The chapter concludes with discussion regarding potential ecosystem impacts due to modern climate change and how modern living things—humans included—will face migration, adaptation, and even extinction as global climate warms and "weirds."

Pleistocene Epoch: Ice advances and retreats on a cold Earth during the "ice ages."

Compared to the Eocene, Oligocene, Miocene, and Pliocene epochs of the Cenozoic fossil parks, visitors are more likely to have heard of the Pleistocene Epoch's ice ages, ice sheets, and mammals such as wooly mammoths, saber-toothed cats, wolves, bison and early humans (including Neanderthals) (Box 3.6). But what happens during an **ice age**? During ice ages, also called **glacials**, ice advances from both poles as global climate, already cool, chills even more (Figures 7.2 and 7.3). Warmer periods between ice advances are called **interglacials;** during such times, the ice retreats back toward the poles (Figures 7.2 and 7.4). Today we are in an interglacial interval following the last glacial advance approximately 21,000 years ago.

Visitors may have seen glaciers on their travels to other national parks like Kenai Fjords NP (Alaska), Glacier Bay NP and Preserve (Alaska), Mount Rainier NP (Washington) or Glacier NP (Montana). The ice age ice sheets were glaciers on a completely different scale—rather than flowing down mountain valleys, they covered continents! At the last glacial maximum two major ice sheets advanced into the United States; the larger, eastern Laurentide Ice Sheet and the smaller, western Cordilleran Ice Sheet (Figure 7.3) (Clark and Mix, 2002). The Laurentide Ice Sheet advanced past Chicago and on the East Coast to southern Pennsylvania, in the process blanketing nearly all of Canada and all of New England. Earlier glacial periods saw ice advance all the way to northeast Kansas! Although none of the Cenozoic fossil parks were covered by ice sheets, sculpting of the current landscape was influenced by changes in river drainages and catastrophic floods during wetter climates of the Pleistocene Epoch (Box 7.1). The story was much the same in Europe. Ice sheets advanced to cover Scandinavia (Norway, Sweden, and Finland), the Baltic Sea and portions of countries bordering the Baltic. The British Isles were under ice as were Greenland and Iceland (Figure 7.2) (Clark and Mix, 2002). Today the ice sheet sits atop Greenland while sea ice covers much of the Arctic Ocean (Figure 7.4). In the southern Hemisphere, the Antarctic ice sheet extended all the way to the edge of Antarctica's continental shelf (Clark and Mix, 2002).

These ice sheets were no mere icy veneer. In North America, the Laurentide ice sheet was mostly between 3,000 ft and 10,000 ft (1,000 and 3,000 m) thick. Imagine ½ to 2 *miles of ice* (Box 7.2)! All the water locked up in continental ice sheets had to ultimately come from somewhere—the oceans. During times of ice advance, global sea levels were reduced by 387 to 443 ft (118 to 135 m) as the glaciers locked up incredible quantities of water (Clark and Mix, 2002). The continental shelf surrounding North America became dry land. Because water depths in the Bering Strait between Alaska and Russia are less than 160 ft (50 m), the Bering Land Bridge was also exposed during glacial periods, facilitating migration (*travel*) between North America and Asia. Ice also descended from mountain glaciers all over the world, leaving plenty of evidence throughout the National Park System.

<u>What caused the ice sheets to advance and retreat?</u>

Two main factors that determine Earth's climate is how the sun's energy reaching Earth is received and distributed and the amount of that energy that is retained by greenhouse gasses in our atmosphere (Box 5.6). One of the main driving factors behind glacial advances and retreats is how the amount of *in*coming *sol*ar radi*ation* (**insolation**) is received at different latitudes. Variations in Earth's orbit (its amount of tilt on its axis, the shape of its orbit around the sun, and the direction its axis is pointed) modify the how insolation is received. These variations produce a climatic pulse on the order of tens to hundreds of thousands of years and are known as the Milankovitch Cycles (Box 7.3; Figures

7.1 and 7.5). Minimum summer insolation at high (65°N) latitudes[8] is thought to initiate the growth of ice sheets. When summer insolation is high enough to melt more snow and ice than falls the previous summer, the ice sheets retreat.

How do greenhouse gasses fit in? The concentration of greenhouse gasses, in particular carbon dioxide (CO_2) and methane (CH_4), in Earth's atmosphere help retain heat energy (Box 5.6). Higher concentrations of these gasses form a "thicker blanket," thus warming climate. Lower concentrations retain less heat, contributing to cooler climates. As measured in Antarctica, there is a lag time of a few hundred years between when ice begins to retreat and when CO_2 begins increase. This does not mean that greenhouse gasses do not play a role in ice sheet advance and retreat! Cooling and warming are initiated by Milakovitch cycles, which are then amplified by subsequent decreases or increases in CO_2, a positive feedback. The exact mechanisms for the changes are not well known but are being extensively researched. Because the oceans are enormous carbon "sponges" able to chemically "soak up" carbon, most proposed mechanisms deal with changes in the connections between ocean circulation, marine biological activity, ocean-sediment interactions, seawater carbonate chemistry, and exchange between the atmosphere and the oceans (Jansen and others, 2007).

Instead of relying completely on interpretations of isotopes in sea-bottom Foraminifera, leaf shapes, and paleosol characteristics (Boxes 5.1, 5.2, and 5.3) to estimate past climate, paleoclimatologists have a more direct method of measurement—the ice itself. Ice cores have been drilled to great depths in both Greenland and Antarctica. Ice cores provide a record of changes in the ice and atmosphere that can be dated with high precision, much like the different fossil layers of rocks in the Cenozoic fossil parks allow paleontologists to reconstruct ancient ecosystems and how they change through time. Bubbles in the ice trap samples of ancient atmosphere that can be chemically analyzed to determine atmospheric composition and greenhouse gas concentrations (Figure 7.6). The European Project for Ice Coring in Antarctica (EPICA) Dome C ice core provides an 800,000 year record of glacial advance and retreat that clearly shows the tie between ice advance and lower greenhouse gas concentrations, as well as ice retreat and higher greenhouse gas concentrations. During the Pleistocene, gas concentrations oscillated between values of 172 and 300 parts per million (ppm) CO_2 and 350 and 800 parts per billion (ppb) CH_4 over eight glacial-interglacial cycles spanning 800,000 years (Figure 7.6) (Loulergue and others, 2008; Luthi and others, 2008).

A pattern developed for the better part of the past three million years. Ice slowly advanced, (in the Northern Hemisphere eventually reaching Chicago or into Kansas) and then retreated back toward the poles (Greenland in the Northern Hemisphere). But the timing and intensity of the pattern has

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[8] This allows snow from previous winter to remain until the next winter, piling up to eventually form glacial ice.

changed through time. From 3 million years ago until 1 million years ago, the oxygen isotope record shows cycles of approximately 41,000 years (Raymo and Huybers, 2008). For the past 1 million years the glacial-interglacial cycle has been 100,000 years (~90,000 years for ice sheets to develop and advance and ~10,000 years to retreat). These ice advances and retreats became progressively more intense. Warmer periods have been warmer, and colder periods colder, particularly over the past 400,000 years (note the higher peaks and lower valleys on Figure 7.6). The causes of this shift in cycle length and intensity are not completely understood.

Between 26,500 and 19,000 years ago ice sheets and glaciers reached their maximum extent (called the Last Glacial Maximum) since the previous interglacial warm period about 120,000 years ago (Clark and others, 2009). In the Northern Hemisphere, the ice then began to retreat as climate began warming about 20,000 to 19,000 years ago (Clark and others, 2009). Temperature reached modern (before the industrial age) levels 11,700 years ago, marking the beginning of the most recent, and still on-going, period of geologic time, the Holocene Epoch (Box 3.2). The next large reduction in northern summer insolation, similar to those that started past Ice Ages, is due to begin in about 30,000 years (Jansen and others, 2007). However, rising greenhouse gas emissions may stifle ice advance for 500,000 years (Archer and Ganopolski, 2005).

Holocene Epoch: After the last ice retreat

The story of our epoch, the Holocene, began like pretty much any other warm interglacial over the past 400,000 years. Ice had retreated back toward the poles and greenhouse gas levels were relatively high (about 285 ppm CO_2 following deglaciation) (Figure 7.5). From this beginning until the start of the industrial age (about AD 1750) climate was fairly stable, CO_2 ranged between 260 and 300 ppm. During the past 1,000 years, the “Medieval Warm Period” (about AD 1100 to 1300) was the warmest period prior to the 1900s (Jansen and others, 2007). The subsequent “Little Ice Age” (about AD 1600 to 1850) is not as well defined but is a period of cooler climate, and glacial advance (although nowhere close to the magnitude of a true glacial period) in the Northern Hemisphere, particularly when compared to the Medieval Warm Period.

This stability started to change as the industrial age began full force in Europe at around AD 1750 and was firmly in place throughout the Old and New worlds by the mid 1800s. **Fossil fuels** such as coal and, later, petroleum products, were burned in increasing quantities. The energy contained within fossil fuels was originally energy from the sun stored in the chemical bonds of organic material (hydrocarbons). Burning fossil fuels breaks those bonds and releases the energy which then powers all manner of mechanical devices. However, it also releases greenhouse gasses (such as CO_2, CH_4, and nitrous oxide N_2O) into the atmosphere. The gasses accumulate in the atmosphere and “thicken the blanket” around Earth, retaining heat, and warming climate. This was the beginning of our modern episode of climate change, referred to as "**global warming.**" Carbon dioxide never attained concentrations above 300 ppm during the 800,000 years prior to AD 1750. During the 258 years between the start of the industrial age and 1958, when CO_2 began to be measured atop Muana Loa volcano in Hawaii, CO_2 jumped to 316 ppm (http://www.esrl.noaa.gov/gmd/ccgg/trends/). In the years since, CO_2 rocketed to 387 ppm by 2009 and continues to increase. Methane has likewise skyrocketed beyond its glacial/interglacial maximum of about 800 ppb to nearly 1,800 ppb (Figure 7.6)! These far out of the "ordinary" greenhouse gas concentrations are contributing to a warming planet.

Earth is now warming; more change is coming

As succinctly stated by the Intergovernmental Panel on Climate Change "Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global sea level." (IPCC, 2007). This is a powerful statement for interpreters. In addition, because it does not mention causes, it implies that we as a society will need to expect ecosystem changes as the climate system continues to warm regardless of cause. This is an important point to make for visitors that may not believe global warming is human-caused. We will have to deal with its effects whether or not global warming is human-caused. However, the scientific consensus is that it global warming is *very likely* (more than 90% certain) human-caused, which also means there can be a human-caused solution!

The burning of fossil fuels is the source of increased greenhouse gas concentrations in the atmosphere, and hence global warming. Although other greenhouse gasses are significant, carbon dioxide will be highlighted here because it is the most important human-produced greenhouse gas (IPCC, 2007). Because we are releasing carbon from long-buried (and "out" of the short-term carbon cycle) coal and oil, this is by definition an unnatural addition of greenhouse gasses to the atmosphere. All of the carbon dioxide does not go straight to the atmosphere. The oceans are a large "sponge" for carbon dioxide and vegetation takes in carbon dioxide as well. But we are pumping unnatural amounts of carbon dioxide into the atmosphere faster than it can be removed, leading to the increase in atmospheric concentrations. This is analogous to filling a bathtub with a narrow drain (Sterman, 2008). If the drain was able to keep up with the faucet, water in the tub would remain at the same level. As long as the faucet pumps out more water than the drain is able to remove, the bath tub fills. The same thing occurs with your checking account! Thus for greenhouse concentrations to begin to decrease we need to not only put less carbon dioxide into the atmosphere, but less than what is removed by natural carbon cycle. Unfortunately, our oceans may be nearing their saturation point, as they take up more carbon dioxide, their acidity is increasing, and they are less able to "soak up" additional CO_2, among other potentially disastrous consequences.

Temperatures are increasing and are projected to continue increasing

As an interglacial, our current geologic epoch (Holocene) is already a period of warmth following the Last Glacial Maximum. But the very recent warming more rapid than has occurred during other interglacial periods. Over the past 100 years, average global temperature has increased by at least 1.3°F (0.74°C) and 11 of the 12 highest recorded global temperatures (since 1850) occurred between 1995 and 2006 (IPCC, 2007) (Figure 7.7). Depending on the emissions scenario, global temperatures could increase (above pre-industrial levels) another 2°F to 11.5°F (1.1°C to 6.4°C) by the end of this century (IPCC, 2007; Meehl and others, 2007). To put this into context, the global temperature difference between ice advancing over Chicago at the Last Glacial Maximum and ice retreating back to Greenland is about 15°F (8°C). This change occurred over approximately 10,000 years. That is about 0.15°F for every hundred years. Projected rates of change for this next century are from 10 to 100 times *faster*! Global warming projections are based on different greenhouse gas emissions scenarios (Box 7.4; Figure 7.8).

Glaciers are retreating world-wide

Projections and measurements of yearly temperature increases seem small, which may make it difficult for people to grasp their significance. In addition, globally-averaged temperature changes are hard to interpret because the effect varies by region. For example, changes will be most pronounced in Arctic regions—temperature will rise more than the global average, and massive amounts of ice will melt. A more dramatic tangible of globally warming temperatures is the rapid retreat of ice sheets and glaciers around the globe. At the last glacial maximum, ice covered approximately one-third of Earth's land (Figure 7.2) (Zemp and van Woerden, 2008). Today permanent ice only covers about one-tenth of Earth's land surface (Lemke and others, 2007). Worldwide, the vast majority of glaciers are retreating (meaning more glacial ice is melting during the summer than is being incorporated into the glacier during the winter) at a rate that has been accelerating since the middle 1980s (Zemp and van Woerden, 2008). The ice sheets of Greenland and Antarctica hold enough ice to raise sea level about 210 feet total (20 ft from Greenland; 190 ft from Antarctica) or 64 meters (7 m and 57 m, respectively) (Lemke and others, 2007). Even relatively small changes in ice sheet volume could strongly affect future sea level and freshwater input to the oceans, potentially driving climate-altering changes in ocean circulation (Lemke and others, 2007). Ocean currents are driven by changes in temperature, salinity, and density. The North Atlantic is a particularly important area for modern ocean circulation. The Gulf Stream carries warm salty water north from the Gulf of Mexico, contributing to the relative warmth of western Europe compared to other cities at the same latitude. In the North Atlantic these waters increase in density as they cool, eventually sinking to great depths and returning south. Increased melting of the Greenland ice sheet provides increased amounts of fresh water to the North Atlantic, potentially decreasing this density differential. Such a decrease could alter the circulation patterns, and potentially affect the climate of western Europe. Global warming and the resultant "freshening" of the North Atlantic will reduce the magnitude of the current over the coming century, although large-scale reduction is not forecast in the next 100 years (but could be a possibility in coming centuries) (Bindoff and others, 2007; Meehl and others, 2007).

Although you cannot see any glaciers from the Cenozoic fossil parks, there are many websites where you can download or view imagery of glaciers around the world. You can actually "watch" selected glaciers retreat via time-lapse photography compiled by the Extreme Ice Survey (www.extremeicesurvey.org, accessed March 6, 2010). Of particular interest to NPS visitors is the retreat of glaciers in Glacier NP. A 2003 study suggested that Glacier NP's glaciers would be completely melted by 2030 (Hall and Fagre, 2003). In a 2009 interview, Daniel Fagre (U.S. Geological Survey) has suggested that based on new models and temperature data, the park's glaciers may be gone *just 10 years from now*, in 2020 (Minard, 2009). The U.S. Geological Survey maintains a large collection of photographs showing the park's glaciers retreating over the past 100 or more years (www.nrmsc.usgs.gov/repeatphoto/overview.htm, accessed March 6, 2010) (Figure 7.9).

<u>Global sea level is rising</u>

As glaciers and ice sheets melt, that water returns to the ocean and is contributing to global increases in sea level. Dramatic examples of sea level rise occurred during deglaciation following ice sheet advance. Sea levels rose by about 390 ft (120 m) following the last glacial maximum between 26,500 and 19,000 years ago (Bindoff and others, 2007; Clark and others, 2009; Clark and Mix, 2002). As climate warms and ice melts, sea level rises. Sea level also "rises" as the water heats up and expands. Detailed measurements of sea levels using tide gauges and satellites show that global sea level rose about 0.12 inches (3 mm) per year since 1993, compared to a 1900s average of about 0.07 inches (1.7 mm) per year (Bindoff and others, 2007). The rate is expected to increase throughout the 21st century and result in global sea levels just over half a foot to two feet (0.18 m to 0.59 m) (Meehl and others, 2007). That may not sound particularly significant, but for a coastal community with an elevation near "0," any increase is significant. Coastal wetlands, like those of Everglades NP with elevations between 0 and 8 ft (2.4 m) would be inundated.

"Global weirding" will amplify the abnormal at the Cenozoic fossil parks

The impacts of global warming go far beyond the temperature increasing, glaciers retreating, and sea level rising, as implied by the term "climate change." The whole host of climatic effects is sometimes referred to as **global weirding** (a coin termed in the 2000s) or, as John Waldman of Queens College put it, "amplification of the abnormal." Such effects include increased frequency of extreme weather events, warmer warm periods, shifts in timing and intensity of precipitation, longer summers and shorter winters. Ecosystems will also face "weirding" as organisms migrate (*travel*), adapt (*evolve*), or go exinct (*die*) The NPS Inventory and Monitoring networks (www.nature.nps.gov/im) are focused on monitoring ecosystem changes throughout the national parks in response to global weirding. Interpreting potential ecosystem responses are the focus of the next section.

The IPCC 2007 reports detail the potential effects of global weirding worldwide and by region (see Box 7.5 for links). In 2009, the U.S. Global Change Research Program produced a publication detailing the regional effects in the United States based upon projections of temperature changes through the end of the 21st century (Karl and others, 2009). The report describes potential changes for each region of the country and can be applied to the Cenozoic fossil parks. Statistics such as glacial retreat and sea level rise are not immediately tangible at the parks, but provide opportunities for broad interpretation that may connect with visitors who live along the coast or in cold, snowy climates.

When interpreting global weirding, it is important to differentiate between **weather** and **climate.** Weather is the day-to-day (or in the cases of the Cenozoic fossil parks, hour-to-hour!) variability of temperature, precipitation, barometric pressure and other atmospheric conditions. Climate represents the long-term average condition for a particular region. Climate change projections of an increase in *average* global temperature of a few degrees are significant even though *daily* weather can swing temperatures tens of degrees each day. In this light, changes in *weather* such as the abnormal blizzards that buried my hometown (Greenbelt, Maryland) and the rest of the East Coast in February 2010 do not provide evidence against *climate* changing. Global weirding is expected to influence weather patterns with more extreme *weather* events as will be shown below.

Global weirding in the Great Plains (Badlands NP, Agate Fossil Beds NM, Fossil Butte NM)

As with most regions in the American West, the greatest weirding will result from water distribution and useage. Karl and others (2009) project periods of extended drought alternating with wetter conditions, particularly in the north, where the fossil parks are. For a paleoecological perspective on the importance of water to the Great Plains, refer to the significance of watering holes like the Big Pig Dig at Badlands NP and the bone beds of Agate Fossil Beds NM. The very wet, subtropical conditions of Fossil Lake at Fossil Butte NM are a particularly stark contrast. In our own times, about 1.5°F (0.8°C) of warming has already occurred, compared to the 1960s and 1970s “baseline.” Projections from the IPCC “lower” and “higher” emissions standards suggest that average temperatures could rise between 2.5°F and 13°F (1.4°C and 7.2°C) by the end of the century. A nearly 4°F (2.2°C) increase is projected by 2020. Cold days will become less frequent. More frequent extreme events (heat waves, drought, heavy rainfall) are likely. The most important factor for the long-term viability of the Great Plains is the health of the region’s major water source: the High Plains or Oglalla Aquifer. Even current water use is unsustainable in the long term. Heat waves, drought and increased temperatures are likely to exacerbate the situation. The dust bowl conditions of the 1930s resulted from poor land use practices, and the overuse of groundwater is a modern example of such a poor practice. Changes in climate and precipitation will affect vegetation zones; an important consideration for a region where range and crop land cover more than 70% of the land surface.

Global weirding in the southwest (Florissant Fossil Beds NM).

Florissant Fossil Beds NM is on the very eastern edge of the report's southwest region, which extends eastward to the Rocky Mountains. Water is the lifeblood of the southwest and after the relatively wet 1980s and 1990s, the current drought (which started in 1999) is the worst in 110 years (Karl and others, 2009). Substantial drops in rain and snowfall, and in turn water supplies, are forecast. Water use is already limited in many areas. The trend will be towards warmer and drier conditions. Like the Great Plains, a temperature increase of nearly 1.5°F (0.8°C) has already been recorded, relative to the 1960s and 1970s. Projections range from temperature increases of just under 4°F (2.2°C) to just over 10°F (5.6°C) by 2100. By 2020, an increase between 2°F and 3°F (1.1°C and 1.7°C) is projected (Karl and others, 2009). The reduction in water and increase in temperature and spread of grasslands may help fuel record wildfires and there is increased chance for long term "megadroughts." Florissant Fossil Beds NM provides a distinctly different paleoecosystem perspective with forests of towering trees and evidence for a succession of lakes.

Global weirding in the northwest (John Day Fossil Beds NM and Hagerman Fossil Beds NM)

Temperature in the Northwest has already increased about 1.5°F (0.8°C) since the 1960s and 1970s, although some areas have experienced a nearly 4°F (2.2°C) increase. Projections suggest that another 3°F to 10°F (1.7°C to 5.6°C) is possible by the end of this century (Karl and others, 2009). This in turn could produce more winter rainfall, instead of snow. Not only will this increase flooding, it will also reduce springtime snowpack—an important source of water for the dry summers in the Mediterranean climate. Both parks are in semi-arid regions of the northwest. Driving through the areas surrounding the parks you will see numerous irrigated fields illustrating the importance of water supplies. The region's important lumber industry is threatened as temperature warms and pests like the pine beetle do not die back during the winters. The sagebrush steppe communities of John Day Fossil Beds NM and Hagerman Fossil Beds NM are also vulnerable to global weirding and will be monitored by the NPS Upper Columbia Basin Inventory and Monitoring Network (UCBN website; http://science.nature.nps.gov/im/units/ucbn/monitor/climate/climate.cfm, accessed March 6, 2010). With a nearly 50-million-year record of climate changes preserved at John Day Fossil Beds NM, past climate changes are particularly evident. Changes from the wetter Pliocene ecosystems at Hagerman Fossil Beds NM to the present show the effects of a drying climate. Projected warming will surpass the temperature of the Hagerman paleoecosystem, which was similar to the modern value (Chapter 5).

Interpreting migration (travel), adaptation (evolution), and extinction (death) in a changing world

The climatic perspective presented at the Cenozoic fossil parks is a great interpretive opportunity to discuss modern climate change. The story of the parks is one of long-term, large-scale climatic cooling from a point where palm trees flourished in Wyoming and Oregon to a world with ice sheets on both poles, poised to advance and retreat on a cold Earth. Visitors and interpreters are surrounded by evidence of very real and very large changes in climate long before any human influence. Some visitors may view this as evidence that global warming and modern climate change is "no big deal" because Earth's climate is capable of wholesale changes outside of human influence. As interpreters it is important to point out that, yes, Earth's climate has been warmer in the past—the Cenozoic fossil parks, particularly the greenhouse parks—archive the evidence of these warmer climates. The core concern with modern climate change is that *we* as a society—all 6.8 billion of us—have never been on an Earth this warm before, with greenhouse gas concentrations this high, and with projections for very rapid continued warming and associated global "weirding." Humans are not just along for the ride on this warming and changing planet, we are quite literally stepping on the gas!

We are not alone. Every other living thing—each adapted to a particular range of ecosystem conditions of *terrain*, *environment*, and *demographics*—is also experiencing a warming, changing planet. As described in Box 6.2, when an ecosystem's *terrain*, *environment*, or *demographics* change outside of the tolerance of an organism, the animal or plant *travels*, *evolves*, or *dies*. The projected global weirding changes listed above are rapidly altering the *environment* (temperature, precipitation) of ecosystems, not just making them warmer. Because each ecosystem component is adapted to their particular range of conditions, ecosystems do not migrate or adapt as one unit. They are each unique assemblages adapted to their current ecosystem conditions at their particular time (Chapters 1 and 5). This is why it is difficult to directly compare modern ecosystems to paleoecosystems—an issue studied in great detail for Florissant Fossil Beds NM (summarized by Meyer [2003]). The Florissant paleoecosystem contains some components that today are associated with subtropical or tropical climates, while others are from more temperate conditions (see Florissant descriptions in Chapters 1 and 5).

During past periods of climate change, populations of animals and plants *travelled* following climatic zones as the zones shifted over long and short time scales. Climate tolerances, mobility (animals), dispersal techniques (plants), lifespan, and availability of resources influence how rapidly species can *travel* (Karl and others, 2009). Reptiles like alligators and crocodiles that lived in the regions of Fossil Butte NM, John Day Fossil Beds NM, and Badlands NP during the Eocene are now found in national parks of the southeast, particularly Everglades NP, 30 to 50 million years later. During the ice ages, changes in animal and plant community distribution are well documented. As you might imagine the presence of an ice sheet over much of the North American continent (Figure 7.3) shifted vegetation communities southward so that tundra vegetation now common in the northern reaches of Canada was located near the southern margin of the ice sheet in Illinois, Indiana, Ohio, and Pennsylvania. As the ice sheet retreated, the range moved northward again (you can watch animations of this following the last glacial maximum for various plants on the NOAA paleoclimate "Pollen Viewer" website listed in Box 7.5). Great Smoky Mountains NP (Tennessee and North Carolina) is celebrated for its biodiversity. The wide variety of species and ecosystems in the park, in part, results from being a "refuge" for plants and animals adapted to cooler, more northern climates. The higher elevations of the park became a home for plants and animals displaced by ice age ice advance. Changes in North American range are already evident in migratory species such as birds and butterflies (Karl and others, 2009). As different organisms migrate to or from different ecosystems, their *demographics* are altered, creating additional stress on the ecosystems. Karl and others (2009) also suggest that Joshua Tree NP (California) and Saguaro NP (Arizona) may contain less and less of their namesake plants, just as Glacier NP is losing its namesake glaciers. Our expanding and immobile infrastructure of cities, transportation corridors, agricultural fields, and dammed rivers, has also altered the *terrain* within and between ecosystems. This infrastructure creates barriers to populations of animals and plants attempting to *travel* in response to ecosystem changes.

Over shorter time scales, populations of plants and animals *travel* to follow the climatic ranges they are adapted for. Over longer (hundreds of thousands to tens of millions of years) time scales climatic changes are a factor in e*volution* and adaptation, as suggested for mammals (Barnosky, 2001, 2005; Barnosky and Kraatz, 2007). Changes visible in the horse family fossils of the Cenozoic fossil parks illustrate this long-term trend of some branches of the horse family tree toward more adaptations for open, grassy ecosystems. Horse feet, teeth and diet, and body size are particularly apparent (Chapter 6). *Evolution* requires lots of time. Generations of reproduction are required for new adaptations to develop and be passed on to successive generations. But current projections show an extremely rapid rate of change. Temperature changes at the high end of the projected changes suggest an increase of 9°F (5°C) over the next century. There is no record of such a rapid rate of climate change anywhere in the past 50 million years—back to the time of Fossil Butte NM paleoecosystems (Jansen and others, 2007). Barnosky and Kraatz (2007) suggest that the rate of climatic change over the next 100 years will likely be faster than rates experienced by mammals over their Cenozoic evolutionary history. With such rapid changes, evolution of new species may not offset the loss of diversity (see below).

Just as the Cenozoic fossil parks offer evidence of *travel*, and *evolution*, they also tell stories of *death* and extinction (Chapter 6). Although extinction is a natural part of life history, global weirding is likely to result in accelerated extinction rates. Unlike periods of climate change recorded in the Cenozoic fossil parks, ecosystems now face man-made barriers to *travel.* In addition, rates of change may exceed populations' abilities to *evolve* and adapt to them. Therefore, *death* (both local and global extinction) is projected to reduce diversity as climate warms. Between 20% and 30% (although regionally the range may be from 1% to *80%*) of species assessed by the Intergovernmental Panel on Climate Change are likely to be at an increasingly high risk for extinction if temperatures increase between 3.6° and 5.4°F (2° and 3°C) above pre-industrial levels (Fischlin and others, 2007). Even more moderate increases in temperature of approximately 2.9°F (1.6°C) above pre-industrial levels—we have already measured temperature increases half that between 1750 and today—could result in extinctions of between 9% and 31% (Fischlin and others, 2007). The International Union for the Conservation of Nature suggests that 36% of assessed vertebrates, invertebrates, plants, fungi and protists are threatened (IUCN, 2009). There have been five major mass extinctions in the past 542 million years, including the "K-T" extinction 65.5 million years ago that helped pave the way for the Age of Mammals (Box 1.3) (Raup and Sepkoski, 1982). The combined effects of habitat destruction and global weirding could be contributing to an on-going sixth mass extinction (Leakey and Lewin, 1996).

Provide visitors interpretive opportunities for revelation and provocation

When interpreting global weirding, I point out that humans like climate pretty much the way it is now. Our evolutionary history is tied to a planet with ice on both poles. We have built our infrastructure, cities, and manage agricultural areas to take advantage of what we consider favorable sea levels and climatic conditions over the past few thousand years. As a society, we will also have to face decisions about where we choose to live (*travel*), adapt to changing conditions (*evolve*) and in some cases may face *death.* This is one of the important lessons that can be learned from the fossil record archived in the Cenozoic fossil parks. Interpreting these universal concepts with regards to climate change is a challenge. All visitors to your park are, to some extent, on vacation, and some may not agree that climate is changing or that humans have anything to do with climate change (Box 7.6; Figure 7.10). This does not mean interpreters should downplay the global significance of climate change and global weirding. Framing change in terms of universal concepts—travel, evolution and adaptation, death and survival—visible in the fossil record can help tie the discussion to the tangible resources at each park. Well chosen statistics (there are numerous sources; see Box 7.5) certainly strengthen interpretation but a long litany of temperature data, percentages, and projections may be too much for some audiences.

Interpretation creates opportunities for an audience to form their own intellectual and emotional connections to the meanings of a resource. Freeman Tilden's principles of interpretation (Chapter 2) further state: "The chief aim of interpretation is not instruction, but provocation" (Principle 2) and "Information, as such, is not interpretation. Interpretation is revelation based upon information" (Principle 4). Climate-change interpretation certainly has the potential to provide visitors with revelations regarding the scope and significance of global weirding, and may also provoke some to action. Regardless of whether a visitor agrees that humans are very likely the main cause of the observed, measured, and projected temperature changes, most would probably agree with stewardship for future generations—a basic tenet of the National Park Service. As stated in the 1916 Organic Act, the National Park Service was established to "…conserve the scenery and the natural and historic objects and the wild life therein and to provide for the enjoyment of the same in such manner and by such means as will leave them *unimpaired for the enjoyment of future generations*." I commonly close climate-change discussions and interpretation with a message that every step each of us takes, no matter how small, towards reducing our own carbon footprint (emissions) and living more sustainably can help us achieve that mission, not just in the national parks. As humans we are adept at adapting and we will need to adapt to coming changes, but also adapt our energy sources and usage. There are numerous sources of information about actions, big and small, that people can take (Box 7.5). The positive message to leave with visitors is that humans already know how to reduce emissions, we already have the technology. It will, however, require a massive investment of money time and energy to implement changes. Kevin Poe, an interpretive ranger at Bryce Canyon NP (Utah) likens this global investment to homeowners insurance. Homeowners pay between 5 and 10 (or more) percent of their income to protect their home against potential threats (fire, hurricane, earthquake, flood, etc.). The global investment to mitigate carbon emissions works out to about 5% of the global Gross Domestic Product (Barker and others, 2007). Is not a 5% investment in our only home (Earth) worth it? Interpretation plays an important role in this in a democracy, where the way to bring about change is to engage the public on the significance of being involved in formulating local and national policy (Sterman, 2008). Some sectors of the public will be more or less receptive to such an idea (Box 7.6).

Climate change is an important part of the story of many NPS areas. The natural resources at the six Cenozoic fossil parks have vast information on past climate change. The more than 217 other areas that preserve fossils also provide a connection to a past climate. The NPS encourages interpretation of past human interactions with climate change. Climate change, in particular drought, is thought to have played a role in the abandonment of ancestral Puebloan settlements at Mesa Verde NP (Colorado) and Chaco Culture National Historical Park (New Mexico. As the brochure *Climate Change in National Parks* (see Box 7.5 for the link) mentions, the NPS administers many areas dedicated to how our nation has responded to major societal challenges from the American Revolution, to the abolition of slavery, to the civil rights movement. Global climate change is a societal challenge that affects not just us as Americans, but all of us as humans.

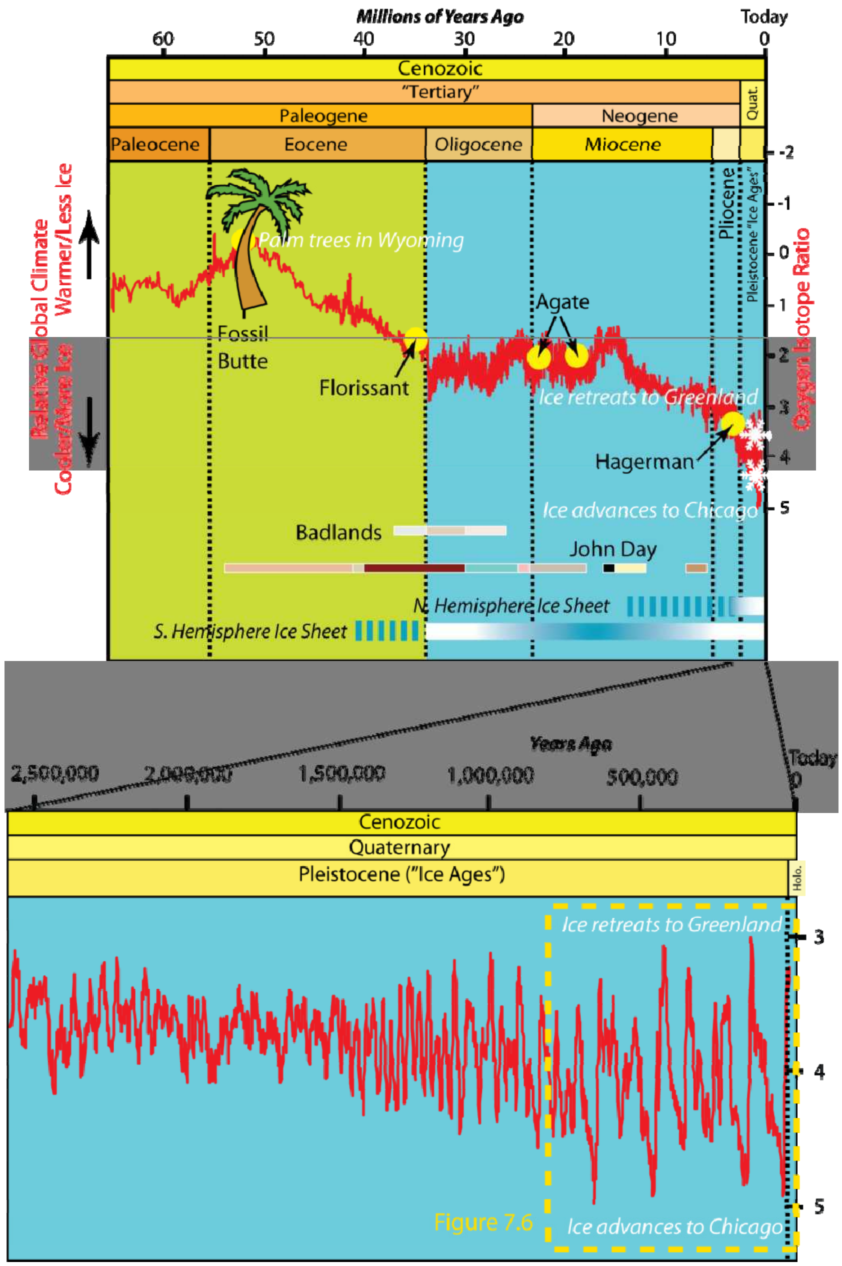
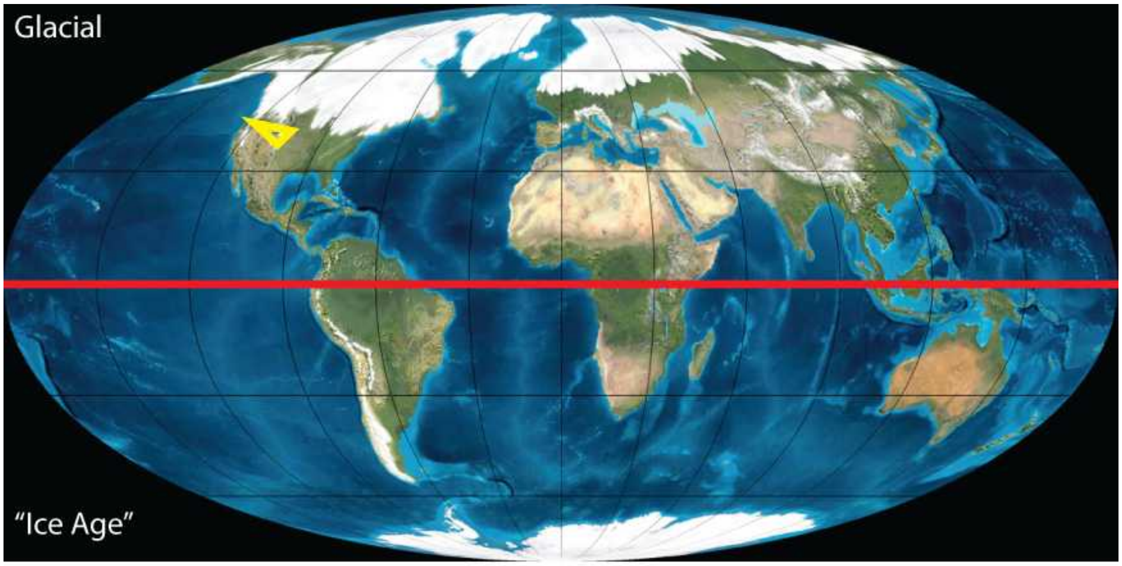


Figure 7.1. The long-term story of global climate cooling and drying in the Cenozoic fossil parks spans from the Eocene palm trees in Wyoming to just before the Pleistocene "ice ages" when ice advanced to Chicago and retreated back to Greenland. The zoom-in section shows the past 2,600,000 years spanning the Pleistocene through today. This is the same foram oxygen isotope record from Figure 5.3 and Box 5.1. Note the scale of the global climate of the "ice ages" compared to the long-term record of change in the Cenozoic fossil parks. There is decreasing frequency but increasing intensity (higher highs and lower lows) of glacial/interglacial cycles. Figure 7.6 zooms in on the past 800,000-year record using ice core evidence. Quat. = Quaternary Period. Holo. = Holocene Epoch (beginning 11,700 years ago and continuing today). (Oxygen isotope data from Zachos and others [2008]. Updated oxygen isotope data downloaded from www.es.ucsc.edu/~jzachos/Publications.html, accessed November, 2009.)



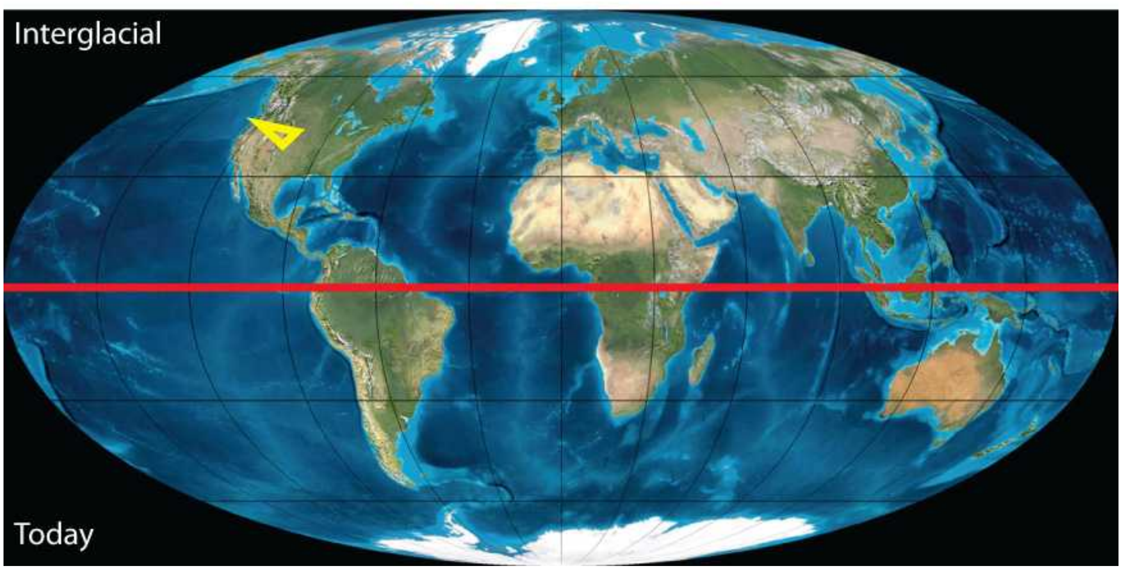


Figure 7.2. Beginning more than 2 million years ago, Earth's climate was cold enough for ice sheets to advance and retreat from the poles. These maps show the extent of continental glaciers during times of ice advance ("ice ages" or glacials) when large areas of the Northern Hemisphere were blanketed with ice. During times of ice retreat (called interglacials, like today), large ice sheets are restricted to Greenland and the Arctic Ocean and Antarctica. Yellow triangle outlines the Cenozoic fossil parks. (Paleogeographic maps modified from and used with permission of Ronald Blakey, Northern Arizona University Department of Geology.)

Figure 7.3. During "ice ages" continental ice sheets advance over Chicago (and Boston, and New York City, and nearly all of Canada). At the last glacial maximum between 26,500 and 19,000 years ago, the Laurentide Ice Sheet was the largest ice sheet in North America. Sea level was about 400 feet lower than it is today, so that most of the light blue colored areas on this map (continental shelves) would have been dry land! Although none of the fossil parks were covered by ice sheets, Badlands NP and Hagerman Fossil Beds NM in particular were shaped by erosion events of the Pleistocene epoch (Box 7.1). (Paleogeographic map modified from and used with permission of Ronald Blakey, Northern Arizona University Department of Geology.)

Figure 7.4. During warmer periods (interglacials) between glacier advances, massive Northern Hemisphere ice retreats to Greenland. As you might imagine, such large ice sheets leave behind evidence of their passing. Piles of glacial debris left behind after the ice melts are called moraines (particularly large ones form the backbone of Long Island and Cape Cod). Glacial gouges, and glacially carved lakes, like the Great Lakes and the hundreds visible in Canada on the map above, provide further evidence of the previous extent of glaciers. Such features also provide evidence for more than one glacial advance. Oxygen isotopes from ocean-bottom Foraminifera (Box 5.1; Figure 7.1) and the ice cores themselves (Figure 7.6) provide evidence of the climatic conditions associated with ice advances and retreats. (Paleogeographic map modified from and used with permission of Ronald Blakey, Northern Arizona University Department of Geology.)

Digging Deeper Box 7.1. Erosion of Badlands NP and Hagerman Fossil Beds NM during the "ice ages."

The giant ice sheets that advanced over northern North America did not cover any of the Cenozoic fossil parks. Nevertheless, erosion during wetter "ice age" climates may have contributed to erosion exposing the fossil-rich layers of the parks. Badlands NP and Hagerman Fossil Beds NM were particularly influenced by such erosion. The Missouri River, just 130 miles (210 km) east of the Ben Reifel Visitor Center at Badlands NP marks the southwestern-most extent of ice sheets in South Dakota. Rivers in the Badlands area flowed north toward Canada's Hudson Bay prior to the ice ages. In response to the presence of huge ice sheets to the north, rivers flowed southward and drained lakes that formed along the edges of the ice sheet (Stoffer, 2003). Rivers like the Missouri cut new gorges at steeper gradients, increasing erosion along their tributaries. Three of the Missouri River tributaries—the White, Bad, and Cheyenne rivers—surround Badlands NP and drain streams that have been carving the "wall" of the Badlands since the ice age switch in drainage patterns. This erosion exposed the unparalleled fossil resources of the park, but will ultimately lead to their destruction and disappearance of the Badlands—in about another 500,000 years.

While the eroded exposures of fossiliferous rock at Badlands NP developed during hundreds of thousands of years of erosion, the steep cliffs of Hagerman Fossil Beds NM were steepened and eroded during a catastrophic flood about 14,500 years ago. During the wetter Pleistocene, ancient Lake Bonneville covered much of western Utah. The Great Salt Lake today is all that remains of this once 325 mile-long (520 km) and nearly 1,000 foot-deep (305 m) lake. The lake overtopped its rim in southeast Idaho and catastrophically flooded the Snake River valley with water volumes reaching an estimated 15 million cubic feet per *second* (Malde, 1968). For comparison, that's more than 150 times the flow over Niagara Falls and about 1.4 times the flow of the Amazon River. The rampaging water ripped out 10 foot-diameter (3 m) boulders of hardened lava flows and strewed them throughout the valley. Visitors to Hagerman Fossil Beds NM can see these boulders, called Melon Gravels, in the Hagerman Valley on the east side of the Snake River. The soft sediments of the Glenns Ferry Formation on the west side of the river also succumbed to severe erosion as the bluffs were steepened, exposing the fossils of animals that were buried in much smaller flash floods 3 million years earlier.

***Digging Deeper Box 7.2*. How thick were the ice sheets?**

The ice sheets that advanced during the ice ages were of nearly unfathomable size. Similar to the deep time example in Box 3.7, humans have a hard time grasping numbers more than a few hundred. Ice sheets in the Northern Hemisphere covered entire countries (Figures 7.2, 7.3, and 7.4) with thousands of feet of ice. The largest ice sheet over North America (called the Laurentide Ice Sheet) was mostly between about 3,000 ft and 10,000 ft (1,000 m and 3,000 m) thick (Clark and others, 1996)!

It is challenging to find a tangible large enough to convey the massiveness of this ice sheet. In the Cenozoic fossil parks fossiliferous bluffs range from about 200 ft (61 m) from bottom to top of Carnegie Hill at Agate Fossil Beds NM to 1,160 ft (350 m) from the John Day River to the top of Sheep Rock across from the Thomas Condon Paleontology Center at John Day Fossil Beds NM. Even though we gaze upward at these bluffs, they are still many times thinner than the ice sheets. The only elevation difference that is close would be those clear days where Pikes Peak summit is visible from Florissant Fossil Beds NM visitor center. Standing at the visitor center and gazing up at the looming summit represents 5,800 ft (nearly 1,800 m) of elevation difference. Even that would be just over half the depth of ice in the thickest areas (2 miles thick!). Visitors who have peered to the bottom of Grand Canyon looked down nearly one mile (1.6 km) to the Colorado River. Imagine that thickness of ice was just average for the continental ice sheets!

***Digging Deeper Box 7.3*. Milankovitch Cycles: Ice advances and retreats as Earth tilts, wobbles, and its orbit changes**

Earth's climate is determined by how the sun's energy (called **insolation** for *in*coming *sol*ar radi*ation*) is distributed, and how much is trapped by our atmosphere. In the middle 1800s, scientists first hypothesized that changes in Earth's orbit influenced the amount of insolation, contributing to the onset of ice ages. In the 1930s, Serbian mathematician Milutin Milanković (incidentally, he performed most of his calculations while in a cell as a World War I prisoner of war) formalized his hypothesis that ice sheets grow when high-latitude (65°N) Northern Hemisphere summer insolation is at a minimum. Why summer? Summer is important because winters are always colder. However, cooler summers allow more of the winter snow to remain. During the next winter, new snow then piles on the left-over snow and the process continues on a large scale, eventually building up to immense quantities of ice. Milanković's mathematic model illustrated how three components of Earth's orbit work together to affect insolation.

The three components are the shape of its orbit around the sun (eccentricity), the amount of Earth's tilt, and the direction its north-south axis is pointing (precession). Their effects are illustrated in Figure 7.5. Each of these oscillates on regular and predictable cycles of different lengths. The eccentricity of Earth's orbit—a measure of how circular the orbit is around the sun—varies on 100,000 and 400,000 year cycles. The amount of Earth's tilt varies between the extremes of 21.5° and 24.5°—today it is in the middle at 23.5°—varies on a 41,000 year cycle. Earth's precession (wobble) varies on a 23,000 year cycle, changing where Earth's axis is pointed (think of a top wobbling and how its axis changes even as the top spins). Through the effects of precession, Polaris (the North Star) was not always as helpful a navigational tool as it is today! Together the three components modulate the amount of solar insolation, creating a "pulse" of climate change during the Pleistocene that influenced the growth of the ice sheets.

The pulse has not been constant and scientists are still working to figure out what caused the change. From 3 million years ago until 1 million years ago, the oxygen isotope record shows cycles of approximately 41,000 years (Raymo and Huybers, 2008). For the past 1 million years the glacial-interglacial cycle has been 100,000 years with warmer warm periods (interglacials) and colder cold periods (glacials) recorded in the oxygen isotope record (Figures 7.1). The 100,000 year cyclicity is a bit puzzling because changes in the shape of Earth's orbit (which varies on a 100,000 year cycle) alone do not have a particularly large affect on insolation. It is thought that the changes in the shape of Earth's orbit can enhance the affects from one of the other variables, particularly precession, when the Earth's orbit places it farther away from the sun during Northern Hemisphere summer.

As mentioned above, the ideal insolation conditions for growing large ice sheets would be a minimum during the summer at high latitudes in the Northern Hemisphere (there is more land in the Northern Hemisphere at higher latitudes to provide a foundation for ice sheets). This would occur when the Northern Hemisphere is tilted at a minimum angle, pointed less directly at the sun (precession) and when summer occurs at a farther distance from the sun (controlled by eccentricity).

The details of eccentricity, tilt, and precession may be a bit much for a short interpretive program. However, if you would like to demonstrate them, a ranger hat makes a handy Northern Hemisphere model (using the brim as the equator, the "peak" of the hat becomes the North Pole). You can use your head as the sun and alter the hat's orientation accordingly (the hat can also spin on your finger) and use your arm to vary the orbit's shape. You can also use volunteers from the audience as orbital actors.

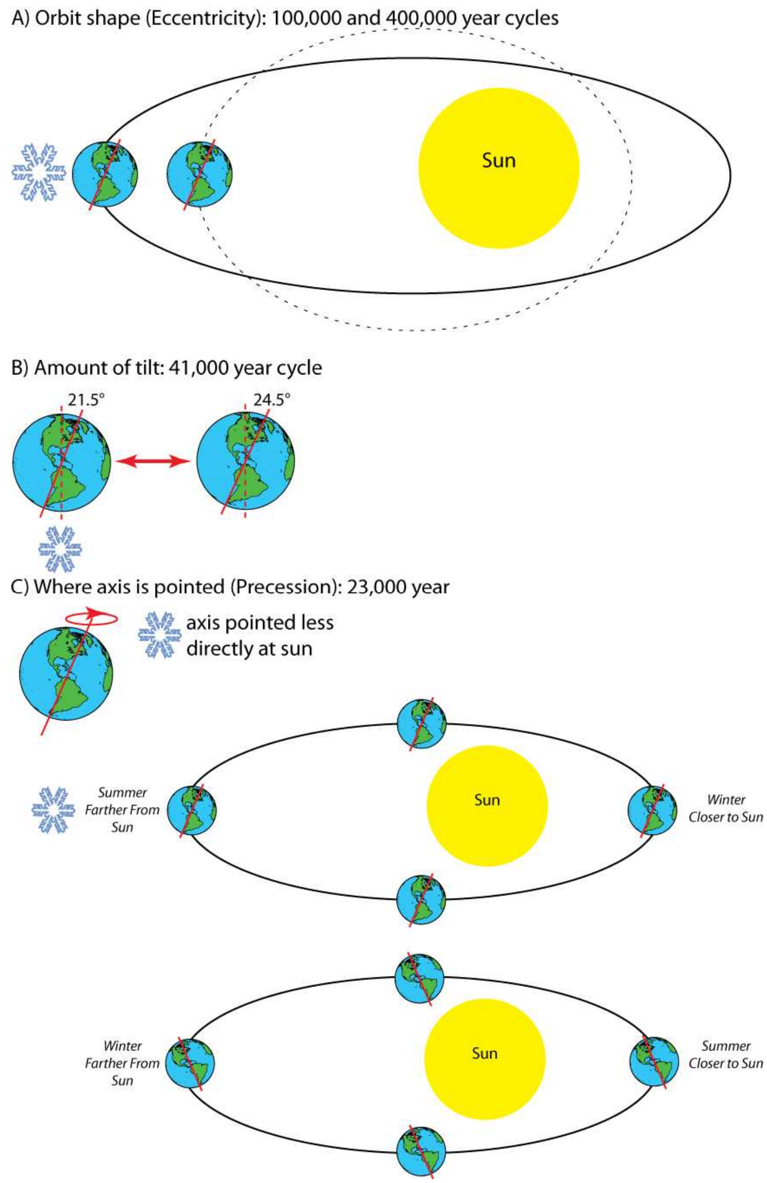


Figure 7.5. For ice sheets to grow, summer **insolation** at 65°N latitude (think Iceland), needs to be at a minimum. The Milankovitch Cycles are variations in characteristics of Earth's orbit that have their own periodicity and together affect insolation as described in Box 7.3. Conditions that minimize summer insolation are indicated with a snowflake icon. A) Variations in how circular Earth's orbit is relate to **eccentricity** (greatly exaggerated in the figure). Eccentricity affects the distance between Earth and the sun. When Earth is close to the sun, it receives more insolation. B) Earth's tilt varies from a minimum of 21.5° to a maximum of 24.5°. Because tilt affects how insolation is distributed from the equator to the poles, it is the reason for our variable seasons. Low tilt means insolation is less direct at the poles. C) **Precession** refers to where Earth's north-south axis (connecting the poles) is pointed. It changes position much like a wobbly top. The precession of the seasons can be affected by eccentricity as shown in the bottom two graphics. Summer insolation is minimized when Northern Hemisphere summer (Northern Hemisphere tilted toward the sun) occurs farther from the sun. Graphics adapted from Dunham (2009).

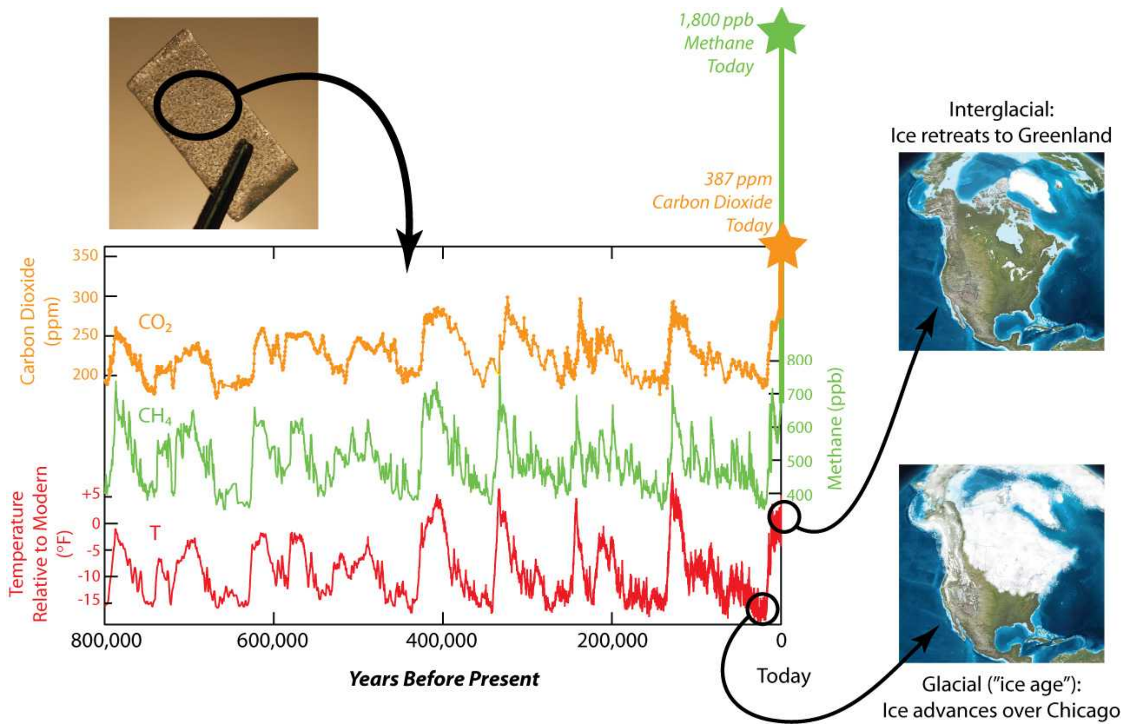
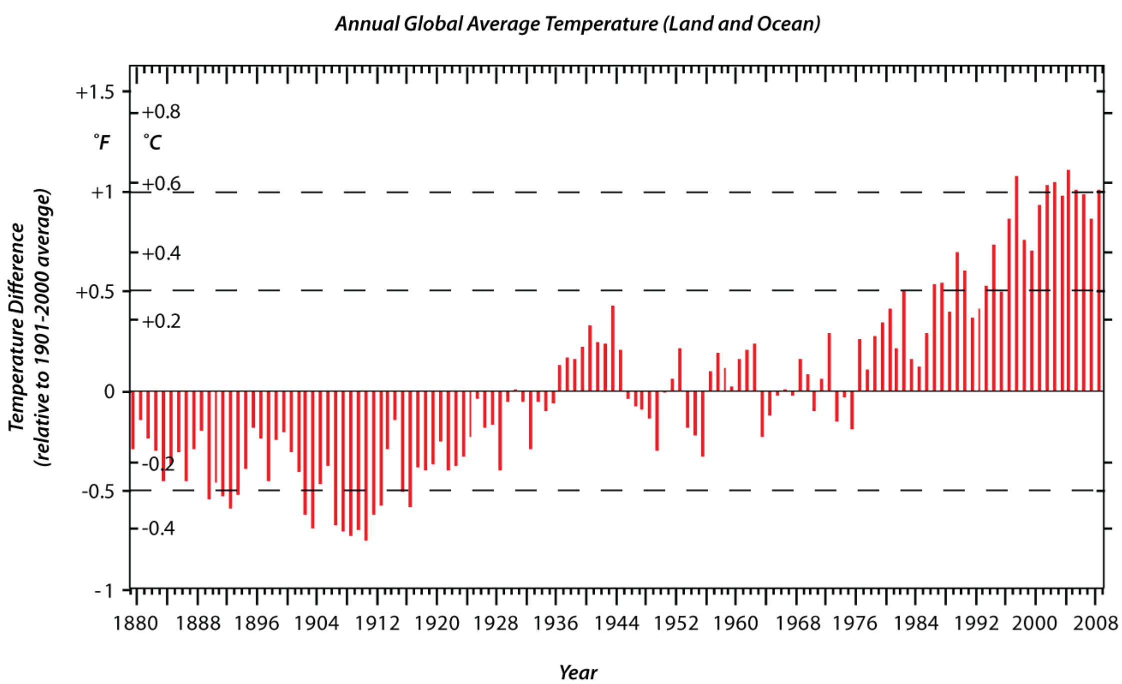


Figure 7.6. Like layers of rock in the Cenozoic fossil parks, layers of ice in ice cores contain an archive of past climate. The photo shows a small (0.8 in by 2 in; 2 cm by 5 cm) slice of an ice core. Bubbles in the ice cores trap samples of ancient atmospheres. Greenhouse gas concentrations can be measured from those bubbles to create graphs such as the one shown here. About 800,000 years of climate records were obtained from a nearly 2 mile (3 km) deep ice core from Antarctica. Carbon dioxide (CO_2) and methane (CH_4) concentrations were measured from gasses trapped in bubbles. Temperatures (T) were estimated using deuterium (heavy isotope of hydrogen) ratios in the ice. Peaks in the data correspond to interglacials (ice retreats to Greenland); troughs correspond to glacials (ice advances over Chicago). Modern concentrations of carbon dioxide and methane are indicated on the far right of the graph—note how they rise so far above the normal glacial-interglacial range. The oxygen isotope ratios from forams (Box 5.1) shows the same pattern (Figure 7.1). ppm = parts per million; ppb = parts per billion.
(Ice core data compiled by Edward Brook [Oregon State University Department of Geosciences] from information in Luthi and others (2008) and Loulergue and others (2008). Modern carbon dioxide and methane concentrations from MacFarling Meure and others (2006), and National Oceanographic and Atmospheric Administration data [www.esrl.noaa.gov/gmd/ccgg/trends]. Ice photo courtesy Edward Brook. Paleogeographic maps modified from and used with permission of Ronald Blakey, Northern Arizona University Department of Geology.)

<u>Digging Deeper Box 7.4</u>. Emissions scenarios project future changes.

In order to project future climate changes, the IPCC utilizes a variety of emissions scenarios to answer questions (hypotheses) such as "if greenhouse gas emissions rise to a particular level, then global temperatures will increase by what amount?" (Meehl and others, 2007). To estimate future temperature increases, IPCC scientists utilized dozens of computer models using four "families" of descriptive emissions scenarios (Nakićenović and Swart, 2000). For example, the A1 scenarios describe a world characterized by very rapid economic growth with a global population peaking in the 2050s and the declining. New and more efficient technologies are rapidly introduced in a world with increased cultural and social interactions. A2 scenarios describe a more heterogeneous world than A1. Self-reliance is a major theme and global population continuously increases. Technological change is slower and more fragmented. B1 scenarios envision a similar "convergent world" as in A1, but an increase in the importance of a service and information economy. Clean and efficient technologies are introduced along with an emphasis on global economic, social, and environmental sustainability. B2 scenarios are characterized by more local emphasis on economic, social, and environmental sustainability with a continuously increasing global population. Figure 1.4 of Nakićenović and Swart (2000) likens these different scenarios to the branches of a tree—rooted in the driving forces of population, economy, technology, energy, and land-use—growing towards global or regional emphasis on economic or environmental priorities. The projections presented by Meehl and others (2007) utilize these basic scenarios. Four of these are summarized in Figure 7.8.



<u>Figure 7.7</u>. Changes in global temperature from 1880 until 2008 relative to the average temperature between 1901 and 2000. Note the continuing upward trend. (National Oceanic and Atmospheric Administration data: www.ncdc.noaa.gov/oa/climate/research/anomalies/index.html#grid, accessed March 7, 2010).

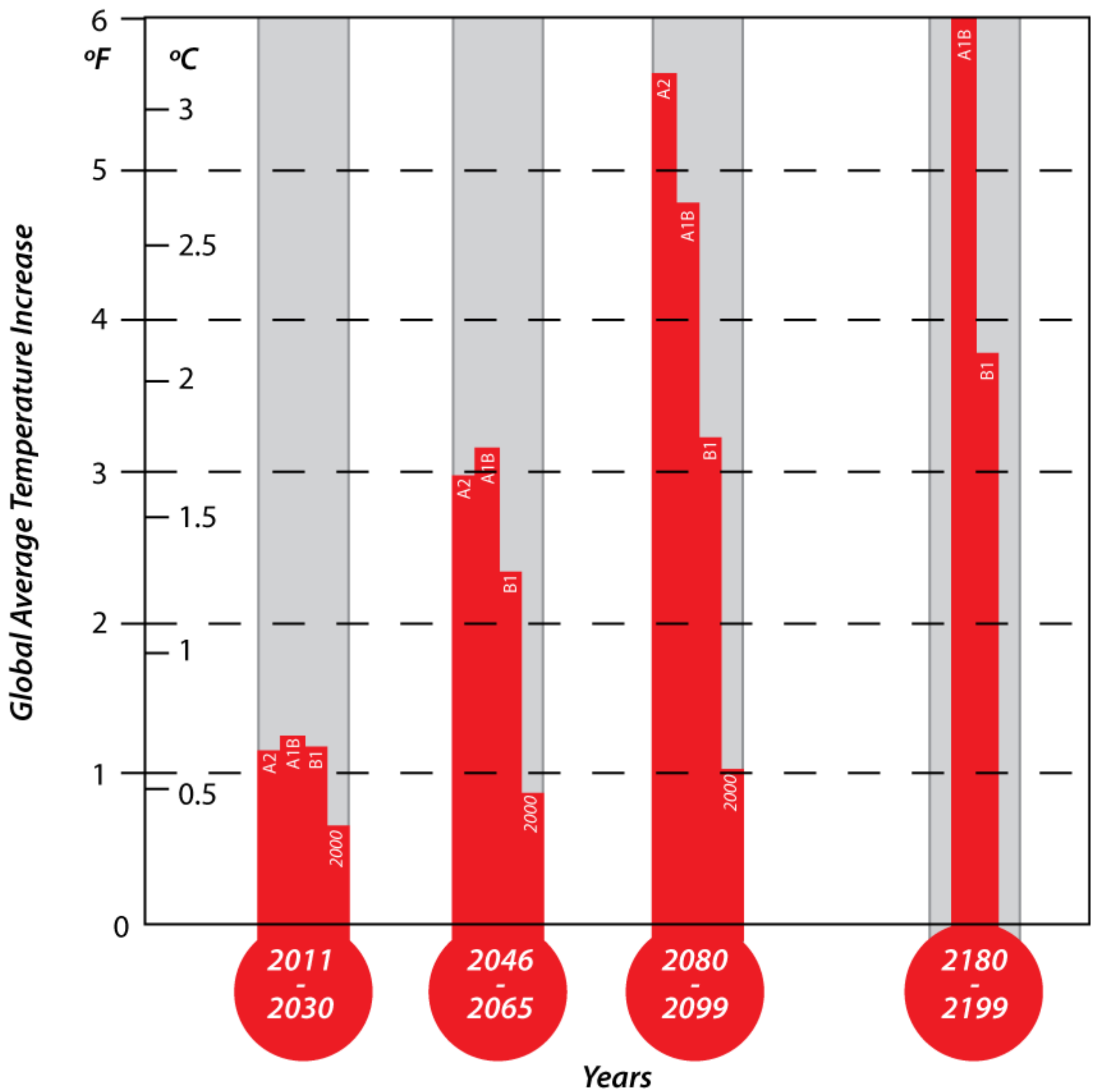


Figure 7.8. These thermometers represent projected increases in temperature over four time periods for four emissions scenarios (Box 7.4). The A2 scenario envisions a heterogeneous world with relatively slow technological change and a continuously growing global population. The A1B scenario envisions a world where new and more efficient technologies are implemented rapidly with a balance of fuel sources (both fossil-intensive, and non-fossil), and a peak in human population in the 2050s, followed by a decline. The B1 scenario envisions a similar population peak, but an economy based more upon service and information, with cleaner, more efficient technologies. The "2000" column represents change that we have already "committed" to, even if greenhouse gas emissions are capped at year 2000 levels. It is important to note that even with capped emissions, temperature will still increase about 1°F over the 21st century. (Based on data in Table 10.5 of Meehl and others [2007].)

Figure 7.9. Repeat photography at Sperry Glacier in Glacier National Park illustrates a global trend of glacial retreat, an indicator of warming climates. The park's namesake glaciers may be completely gone as early as 2020. Photo pairs like these are available online for many glaciers in Glacier NP: www.nrmsc.usgs.gov/repeatphoto/overview.htm, accessed March 6, 2010. (1913 photo by W.C. Alden, courtesy Glacier NP archives; 2008 photo by Lisa McKeon, U.S. Geological Survey).

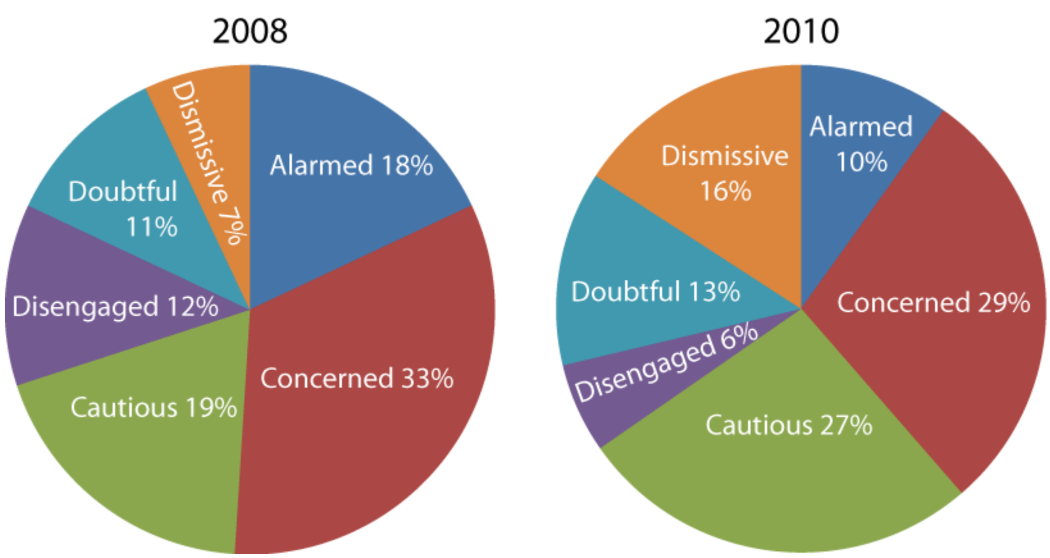


Figure 7.10. Global warming's "six Americas." Surveys of more than 2,000 adults in the United States in 2008 and more than 1,000 in 2010 reveal percentages of people in each of six categories. Beginning with "Alarmed" (highest belief in global warming/most concerned/most motivated) levels of belief in global warming, concern and motivation decrease clockwise to those that are "Dismissive." Notice how the number of "Alarmed" adults has *decreased* by nearly half while the number of "Dismissive" adults has *more than doubled* in two years. Knowledge of these different audience types may lead to more effective interpretive programs (Box 7.6). Data from Leiserowitz and others (2010) and Maibach and others (2009).

***Digging Deeper Box 7.5*. Where to go for more information**

This chapter provides a basic overview of modern climate change. Googling "climate change" returns nearly 52,000,000 hits, so there is plenty of material out there. Here are a few of the websites I have find particularly helpful for "digging deeper." As with any information gathering on the internet, be aware of the source. These links were current as of April, 2010. Appendix B contains additional links to websites that provide information on other topics discussed in the manual.

Intergovernmental Panel on Climate Change (IPCC). The definitive scientific assessment of climate change, their last report was published in 2007. Research since then suggests that some of their projections may be too conservative. *www.ipcc.ch.* The 2007 reports that formed the foundation for this chapter can be found here:
www.ipcc.ch/publications_and_data/publications_and_data_reports.htm#1

Primary Literature. Scientific, peer-reviewed journals such as *Nature* and *Science* publish current research regarding climate change. You have access to these journals (except for issues from the past 1 year) through the Department of Interior online library, from any NPS computer. *http://library.doi.gov/electronic/index.html*

Real Climate Blog. Scientific discussion and commentary by climate scientists with links to multiple sources of information. *www.realclimate.org*

Climate Literacy. Interagency booklet and poster describing the basic tenets of climate science and climate change. *www.climatescience.gov/Library/Literacy*

NPS Climate Change Response Program. Source for climate change information, including many NPS-specific links. *http://nature.nps.gov/climatechange/*

Climate Friendly Parks. NPS efforts to increase sustainability and promote climate change awareness Servicewide. *www.nps.gov/climatefriendlyparks*

U.S. Global Change Program. Clearinghouse for reports and data regarding climate change in the U.S.: *www.globalchange.gov* The impacts of climate change report (Karl and others, 2009) referenced in this chapter can be found here: *www.globalchange.gov/publications/reports/scientific-assessments/us-impacts*

Extreme Ice Survey. Dramatic photos and time lapse footage of retreating glaciers worldwide. You can also download their Google Earth layer. *www.extremeicesurvey.org*

Global Warming's Six Americas. Download reports and information regarding the six American audiences for global warming. *www.climatechangecommunication.org*

Environmental Protection Agency (EPA). Links to many information sources regarding climate change and U.S. policy, also contains suggestions for what you can do to reduce your carbon footprint. *www.epa.gov/climatechange*

National Aeronautics and Space Administration (NASA). View Earth's up to the minute "vital signs" regarding changing climate. Spectacular imagery and animations. *http://climate.nasa.gov*

National Oceanographic and Atmospheric Administration (NOAA). Download various paleoclimate data and information from the National Climate Data Center: *www.ncdc.noaa.gov/oa/ncdc.html.* Watch Pollen Viewer animations here: *www.ncdc.noaa.gov/paleo/pollen/viewer/webviewer.html*

***Digging Deeper Box 7.6*. Interpreting climate change to global warming's "six Americas."**

During the summers of 2007 and 2008, more visitors challenged me on climate change than on the age of the Earth or evolution. There is no one "right" way to deal with visitors who disagree. Studies of American adults in 2008 and 2010 by the Yale Project on Climate Change and the George Mason University Center for Climate Change Communication yielded six audiences for climate change discussion (listed here in decreasing levels of awareness and concern): Alarmed, Concerned, Cautious, Disengaged, Doubtful, and Dismissive (Leiserowitz and others, 2010; Maibach and others, 2009). These publications, available online, provide a very detailed audience analysis of the demographics of each group.

Descriptions below are from Maibach and others (2009). An earlier survey in 2007 resulted in suggestions for how to engage the "six Americas" (Leiserowitz and others, 2008) as summarized below.

The "Alarmed" feel that global warming is real and humans are causing it. They are ready to respond to climate change and are looking for clear "actionable" suggestions regarding what they can do to be part of the solution. Messages regarding the dangers of climate change for people around the world, for future generations, and other species are likely to be well-received.

The "Concerned" think that global warming is real and human-caused but worry less about it. Emphasizing local impacts is particularly important as this group may see climate change as happening elsewhere. Messages regarding human health impacts may also resonate with this group.

The "Cautious" are less convinced that global warming is happening and more than one-third believe there is a lot of disagreement among scientists over whether global warming is happening. Outreach efforts to this group should emphasize the strong scientific agreement that harmful, human-caused global warming is occurring. Efforts should also emphasize that we as a nation and we as individuals can make a difference.

The "Disengaged" (the 2008 report refers to this segment as "Unconcerned") are not sure that global warming is happening and are the group most likely to change their minds. Slightly more than one-third believe human activities are the primary cause and a majority do not know enough to say whether scientists are in agreement. Like with the "Cautious," outreach efforts should emphasize the strong scientific agreement regarding the reality and impacts of climate change.

(***continued on next page***)

<u>Digging Deeper Box 7.6 (continued)</u>. Interpreting climate change to global warming's "six Americas."

The "Doubtful" do not know if global warming is happening or not, but the issue is not important to them. Most believe there is significant disagreement in the scientific community and that if global warming is happening, natural causes are likely to blame. Outreach efforts should also emphasize the strong scientific agreement and that humans commonly take action to protect against uncertain threats (home, car, and life insurance, for example). Another method may be to not mention global warming and focus on economic benefits of conservation, such as freedom from dependence on foreign oil.

The "Dismissive" are sure global warming is not occurring, will not impact their lives (or future generations), and is therefore unimportant. They are unlikely to change their views. Most believe there is a lot of disagreement in the scientific community and more than 20% believe there is a scientific consensus that global warming is *not* happening. Some may even believe climate science is a "hoax." This group is extremely hard to reach because of their distrust of the media, the government, and environmental organizations; thus interpretation by a federal government employee such as an NPS interpreter may be quickly dismissed. They may, however, support a clean-energy economy if it means freedom from foreign oil. It is important not to put down their beliefs when interpreting to other segments.

Obviously you cannot tell just by looking at someone or a group of visitors which one of the six Americas they fall into. As you interact with them, it may become more apparent, and if there is more than one person, they may fall into more than one audience. Because of the differences between the "six Americas," it can be challenging to do an entire program focusing on global warming. Integrating information regarding global warming, climate change, and global weirding into other programs and interpretive opportunities may help "doubtful" or "dismissive" visitors feel still feel engaged with the main themes of the program. Although the approaches vary, remember that interpreters respect all visitors and create opportunities for visitors to form their own intellectual and emotional connections. For those who have questions or concerns apart from the rest of the audience, offer to stick around for a few minutes to discuss things one-on-one if you have the time.

CONCLUSION

One of my favorite quotes regarding the perception of geology and the importance of geologic interpretation comes from geologist James L. Dyson of Lafayette College (Pennsylvania). Dyson began his book "The Geologic Story of Glacier National Park" (1957, Glacier Natural History Association) with these words:

> Until recently a geologist was visualized by most people as a queer sort of fellow who went around the countryside breaking rocks with a little hammer. Fortunately, the general public today has a much clearer picture of the geologist and his science, but there are still many among us who mistakenly feel that geology is something too remote for practical application.

More than fifty years later, this perception still rings true. In this light, I have attempted to present the interconnected geological and paleontological stories of the Cenozoic fossil parks—Fossil Butte NM, John Day Fossil Beds NM, Badlands NP, Florissant Fossil Beds NM, Agate Fossil Beds NM, and Hagerman Fossil Beds NM—with practical and tangible interpretive aspects. The manual is set up with each chapter being self-contained but cross-referenced to other chapters to find additional information. "Digging Deeper" boxes are found throughout and provide more detailed information and interpretive suggestions. For interpreters just getting started with paleontology, or for those who are looking for some additional content for a program, the first three chapters provide a foundation of basic paleontology knowledge for the six Cenozoic fossil parks. The scope and significance of the tremendous fossils found in all six parks is described in Chapter 1. Chapter 2 summarizes National Park Service interpretive theory in a general sense but also provides suggestions for discovering information about your audience and developing tangibles, intangibles, and interpretive opportunities in a fossil park. Chapter 3 suggests interpretive answers to three common types of visitor questions that provide opportunities to connect visitors to the Cenozoic Era, fossilization processes, and the power of interpreting fossils in the same place where they were originally found.

The next three chapters tell the stories of the evolving ecosystems of the Cenozoic fossil parks, focusing on changes in landscape, climate, and life. Chapter 4 connects the sedimentary rocks the fossils are buried in, to the rising mountains and erupting volcanoes of the American West. Chapter 5 places the parks in chronological order in the context of greenhouse and icehouse global climates. The horse family is the focus of Chapter 6, which provides an interpretive link to how populations of organisms respond to ecosystem change through migration (*travel*), adaptation (*evolution*), and extinction (*death*). The final chapter of the manual continues the story beyond Hagerman Fossil Beds NM—the youngest of the Cenozoic fossil parks—as ice alternately advanced over Chicago and retreated to Greenland. Modern, human-caused, climate change is a chapter we are all writing. As our collective home warms, all living things—including humans—will be faced with migration, adaptation, and perhaps even extinction in response to "global weirding." The Cenozoic fossil parks are particularly appropriate venues for climate change interpretation because visitors and interpreters are surrounded by evidence of natural climate change and ecosystem evolution over the past 55 million years. Climate change interpretation may help visitors relate to modern climate change and appreciate our collective impact.

I thoroughly enjoyed my time sharing the interconnected stories of the Cenozoic fossil parks with visitors. These parks span the time between the movies “Jurassic Park” and “Ice Age.” I was able to tell the stories of a time most visitors are not familiar with, but certainly, as mammals, are a part of. Most visitors I interacted with were excited to not only learn about the park they were visiting, but also to hear about other parks that help tell “the rest of the story.” I hope interpreters will find this manual useful when planning a program. Trying to fit it all into one program or interpretive opportunity will be way too much! Feel free to use what works for you and let your individual passions drive your interpretation. That spark will catch fire! Enjoy your time at these parks and sharing their stories with visitors. By forging connections with visitors, interpreters help visitors care *about* the parks so that they may then care *for* the parks and assist them in preserving the past for future generations.

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GLOSSARY

Etymologies ("word origins") taken from various sources, primarily Brown (1956).

absolute dating. Technique whereby radiometric decay, fission tracks, or other measureable rates are used to determine the numerical age of a fossil or rock (For example: "This fossil is 34 million years old").

accreted terrane. A large body of rock such as an island chain or microcontinent, manufactured elsewhere, that smashed into (accreted onto) the **craton** of a continent, expanding the continent outward. Most of the West Coast of the United States was built out by accreted terranes over the past 200 million years.

alluvial fan. A fan-shaped sedimentary deposit formed when streams carrying sediment flow out of a highland area to an adjacent lowland. They lose speed (and the ability to carry heavy material) at this transition and deposit their sedimentary load.

ammonite. A squid-like marine invertebrate with a coiled shell. Common in the Western Interior Seaway sediments in Badlands NP. Ammonites went extinct at the end of the Mesozoic Era.

anthropogenic. Describes something that is human-caused, or related to human activity. Etymology: *anthropos* (Greek meaning "man") + *genesis* (Greek meaning "origin").

Archaeohippus. Very small ("dwarfed") Miocene-aged tridactyl horse. Originally named for specimens from the Mascal paleoecosystems of John Day Fossil Beds NM. Etymology: *archaios* (Greek meaning "from the beginning" or "old") + *hippos* (Greek meaning "horse").

assemblage. A group of fossils found in the same **stratigraphic** layer or associated layers.

atom. The fundamental building blocks of elements. Atoms have a nucleus of protons and neutrons surrounded by a cloud of revolving electrons.

badlands. Generic term for low, rounded, erosional landforms, that are sparsely vegetated. Common in semi-arid ecosystems around the world. Using the term with a capital "B" refers to Badlands NP.

basalt. A dark-colored **lava** very low in silica, which makes it fluid and runny.

basement. Generic term for the very old (in the American West these rocks are commonly Precambrian, older than 545 million years old) rocks that lie beneath younger sedimentary rocks. Usually basement rocks are were previously molten (**igneous rocks**) or were altered by high pressure and temperature (**metamorphic rocks**).

basement uplift. A type of mountain building process where compressional (pushing together) tectonic forces move ancient igneous or metamorphic rocks ("**basement** rocks") toward the surface along faults that are quite steep near the surface.

bear dog. A carnivorous dog-like predator and scavenger found in Miocene-aged rocks of John Day Fossil Beds NM and Agate Fossil Beds NM. Although they looked like dogs, they are in the same **family** as bears and weasels, hence their name.

bed. See "strata."

biochronology. A dating technique in which the overall fossil **assemblage** is used to determine the age of a rock layer.

body fossil. A fossil representing remains of an actual part of an organism: bones, teeth, shells, leaves, flowers, fruits, nuts, woods, etc. Compare to **trace fossil.**

bone bed. Sedimentary layer containing exceptionally abundant vertebrate fossils, bone and bone fragments. The Fossil Hills quarries at Agate Fossil Beds NM uncovered particularly good examples.

brachydont. Describes a tooth that is not much taller than it is wide. Browsers typically have brachdont teeth, which are used to snip leaves rather than grind them. Etymology: *brachys* (Greek meaning "short") + *odon* (Greek meaning "tooth").

brontohere. See "titanothere."

browser. An herbivorous animal that primarily eats leaves of trees or shrubs rather than grass.

chalicothere. See "*Moropus*."

chemical sedimentary rock. A sedimentary rock formed when dissolved material precipitates out of water and is deposited.

chemical weathering. A process by which chemical reactions dissolve Earth material.

clast. A fragment or grain of rock formed by physical breakdown of a larger rock. Clasts can be cemented together to form **clastic sedimentary rocks**.

clastic sedimentary rock. A rock made up of fragments of other rocks (**clasts**) that are cemented together.

claystone. A sedimentary rock composed of very fine (clay-sized) particles.

climate. Long term (years or longer) average of a region's meteorological conditions such as temperature, precipitation, wind, and atmospheric pressure.

compression/carbonization. Fossilization process by which unstable organic material is squeezed out of an organism's remains, leaving behind a carbon-rich (dark-colored) residue, outlining the shape of the organism. Enables fantastic preservation of fish and plant fossils in lake paleoecosystems of the Cenozoic fossil parks, particularly at Fossil Butte NM, John Day Fossil Beds NM, and Florissant Fossil Beds NM.

conglomerate. A sedimentary rock composed of fragments of particles larger than 0.08 in. (2 mm) in a matrix of smaller particles. Usually deposited in a river or along coastlines with high wave energy.

continental platform. The undeformed core of North America. Far removed from tectonic activity for hundreds of millions of years, it exhibits a relatively flat landscape. Much of America's heartland and the Midwest is part of the continental platform. Also called the **craton.**

coprolite. A type of **trace fossil** representing fossilized feces. Fossilized fish (and even crocodile) poop is particularly common at Fossil Butte NM. Etymology: *kopros* (Greek meaning "dung") + *lithos* (Greek meaning "stone").

Cordillera. The broad, mountainous region of western North America stretching from the Front Ranges of the Rocky Mountains (just west of Denver) westward to the Pacific Ocean.

***Cormohipparion*.** Etymology: *cormo* (Greek meaning "tree trunk") + *hippos* (Greek meaning "horse") + *arion* (Greek suffix meaning "dimunitive")

craton. See “continental platform.”

crystal. A solid mass of a chemical element, compound, or mixture with a consistent composition and an orderly arrangement of atoms.

Daemonelix. Literal translation is “hostile” or “dreadful trench”, they are more commonly called the “devil’s corkscrews,” referring to the spiral-shaped burrows of *Paleocastor* (ancient land beaver). Agate Fossil Beds NM preserves many examples of these distinctive trace fossils.

Daeodon. A genus of the mammal **entelodont**. The specimens from Agate Fossil Beds NM are the largest, last, and best-preserved in North America. Commonly, but incorrectly, called “*Dinohyus.”* Etymology: *daeo* (Greek meaning “hostile” or “dreadful”) + *odon* (Greek meaning “tooth”)**.**

Daphoenodon. A genus of bear dog found at Agate Fossil Beds NM. Etymology: *daphoeno* (Greek meaning “blood-red” or “gory”) + *odon* (Greek meaning “tooth”).

deep time. Refers to time on a geological, rather than human or historical, scale. The term refers to incomprehensibly long (millions of years) time, and was popularized by John McPhee in his 1981 book *Basin and Range*.

depositional environment. Refers to the physical setting in which sediment was deposited. In the Cenozoic fossil parks, depositional environments can be broadly classified as **fluvial**, **lacustrine**, **eolian**, or **lahars**.

eccentricity. A description of how circular Earth’s orbit is. High eccentricity results in a less circular (more elliptical) orbit. Eccentricity is one of the three characteristics of Earth’s orbit (along with tilt and precession) that influence climate over a periods of thousands of years.

element. The fundamental building blocks of minerals. Atoms make up elements, which combine to form minerals. Assemblages of minerals make up rocks.

entelodont. Fearsome, omnivorous, mammalian scavengers up to 2 m (about 6 or 7 ft) at the shoulder. Found in North America during the late Eocene through early Miocene. ***Daeodon*** (commonly called *“Dinohyus”*) found at Agate Fossil Beds NM are the last, largest, and best preserved entelodonts in North America. They are also common in John Day Fossil Beds NM and Badlands NP, where the “Big Pig Dig” (1993–2008) was named after them. Etymology: *entelos* (Greek meaning “perfect”) + *odon* (Greek meaning “tooth”); refers to the perfect “bunodont” dentition of the upper and lower cheek teeth that are divided more or less into four quadrants with rounded cusps. Your molars are also “bunodont.”

eolian. Pertaining to the wind. Eolian (also spelled Aeolian) sediments (sand, silt) are those blown and around and redeposited by the wind, such as sand dunes.

eon. The largest division of geologic time. **Epochs** make up **periods** make up **eras** which make up **eons**. For example the Miocene Epoch is part of the Neogene Period, which is part of the Cenozoic Era, which is part of the Phanerozoic Eon.

Epihippus. A genus of small-dog sized, four-toed horse. Found in the Clarno paleoecosystems of John Day Fossil Beds NM. Etymology: *epi* (Greek meaning “upon,” “over,” or “on”) + *hippos* (Greek meaning “horse”).

epoch. A division of geologic time, the Eocene, Oligocene, Miocene, and Pliocene preserved in the Cenozoic fossil parks are examples of epochs. Epochs make up **periods**, which make up **eras** which make up **eons**. For example the Miocene Epoch is part of the Neogene Period, which is part of the Cenozoic Era, which is part of the Phanerozoic Eon.

Equidae. The horse family. Today the horse family includes 8 species of horses, zebras, and donkeys in one genus—*Equus.* Equidae fossils are found in each of the Cenozoic fossil parks and represent at least 15 genera of equids.

***Equus*.** The modern horse genus. It also encompasses donkeys and zebras. The earliest species of this genus is *Equus simplicidens,* the Hagerman Horse of Hagerman Fossil Beds NM. Etymology: *equus* (Latin meaning "horse").

era. A major division of geologic time, the Paleozoic, Mesozoic, and Cenozoic eras are delinated from each other by mass extinction events. Epochs make up **periods** make up **eras** which make up **eons**. For example the Miocene Epoch is part of the Neogene Period, which is part of the Cenozoic Era, which is part of the Phanerozoic Eon.

extant. Refers to an organism still alive today. Etymology: *extant* (Latin meaning "to stand out").

extinction. Refers to the death of all populations of a taxonomic group. Etymology: *extinguo* (Latin meaning "put out," "quench," "destroy," or "annihilate"). Mass extinctions are those that affect many different taxonomic groups at the same time, geologically.

fact. A confirmed observation (Scott, 2004). Facts are the building blocks of scientific knowledge.

family. A rank in the taxonomic classification scheme (see "taxonomy") above genus. Equidae (horse family) is an example found throughout the Cenozoic fossil parks.

fanglomerate. A sedimentary rock consisting of material originally deposited in an **alluvial fan** that has been cemented into solid rock.

fault. A break in a body of rock in which one side has slid relative to the other.

fluvial. Referring to a river or river processes.

fold and thrust belt. A deformed region of Earth's crust characterized by the bending (folding) and sliding (thrust faulting) of sedimentary rocks while the underlying **basement** rocks are undeformed. Results from compressional (pushing together) tectonic forces. Fossil Butte NM is on the eastern-most edge of a fold and thrust beld.

foraminifera. A tiny amoeba-like, single-celled organism that makes a "shell" called a test. Oxygen isotopes in foraminifera (or foram) tests provide a nearly continuous global record of temperature and ice volume, making them an invaluable source of data regarding past climates. Etymology: *foramen* (Latin meaning "hole") + *fero* (Latin meaning "to bear")

foreland basin. A depressed region adjacent to an area where mountains are rising. Foreland basins receive sediment eroded from the nearby mountains. Badlands NP and Agate Fossil Beds NM are located in a large foreland basin that received sediment from the eroding Black Hills and Rocky Mountains, respectively.

formation. A body of rock that extends over a relatively large area. Its distinctive characteristics (rock type, fossils, etc.) allow geologists to name and describe it, map its distribution in the region, and correlate it with regions that have similar rocks. Can be subdivided into **members** or grouped together into **groups**.

fossil. Any evidence of past life preserved in a geologic context. Fossils are grouped into two major categories: **body fossils** and **trace fossils**.

fossil bed. Layer of sedimentary rock that preserves **fossils**.

fossil fuel. Generic term for any hydrocarbon (such as petroleum products, natural gas, coal) that can be burned for fuel. The energy in hydrocarbons is stored in chemical bonds formed in ancient organic material ("fossils"). Increases in greenhouse gas concentrations from burning fossil fuels is the primary cause of **anthropogenic** global warming.

genera. Plural of the term **genus**.

genus. A rank in the taxonomic classification of organisms. The genus and species together form the standard nomenclature for a living or fossil organism, with the genus capitalized and listed first. For example, the genus and species of humans is *Homo sapiens.* See "taxonomy."

geologic context. The rock type and other fossils found in association with a fossil that provide clues to the ancient environment. The geologic context is important to determine the story behind the remains of a fossil.

glacial. Descriptive term for any object or process related to glaciers. Also used as a term to signify times of advancing glaciers ("ice ages") during the Pleistocene Epoch. Also see "interglacial."

global warming. The average increase Earth's surface and low atmosphere temperature, usually used in reference to **anthropogenic** activities.

global weirding. Term coined in the 2000s to describe the collective impacts of global warming such as increases in temperature, hotter high temperatures, colder low temperatures, changes in patterns and frequency of precipitation and storms.

grazer. An herbivorous animal that feeds primarily on grasses.

group. A grouping of associated geologic **formations.**

half life. The amount of time it takes for half of the atoms of a **radioactive** parent **isotope** to undergo **radioactive decay** to a stable daughter isotope.

Haplohippus. A small-dog sized, four-toed, browsing horse from the Eocene. Found in the Clarno paleoecosystems of John Day Fossil Beds NM. Etymology: *haplos* (Greek meaning "simple") + *hippos* (Greek meaning "horse").

hotspot. A plume of hot Earth material rising from deep within Earth's mantle. Yellowstone's geothermal features are fueled by a hotspot. The Columbia River Basalts exposed within John Day Fossil Beds NM may represent the initial surfacing of the Yellowstone hotspot. Volcanoes in Hawaiian national parks were fueled by the Hawaiian hotspot.

***Hypohippus*.** A very large, for its time, specialized browsing horse. This tridactyl horse existed during the early and middle Miocene. Found in the Mascall paleoecosystems of John Day Fossil Beds NM. Etymology: *hypo* (Greek meaning "beneath," "less than," or "somewhat") + *hippos* (Greek meaning "horse").

hypothesis. A statement of the relationship among things (Scott 2004), usually phrased as an "if…then" statement.

hypsodont. Describes a tooth that is much taller than it is wide. Grazers typically have hypsodont teeth, which facilitates grinding very abrasive foods like grass. Etymology: *hypsos* (Greek meaning "high") + *odon* (Greek meaning "tooth").

***Hyracotherium*.** The oldest genus in the horse family (**Equidae**), dating back to the early Eocene, about 55 million years ago. The genus has been split into at least six different genera but "*Hyracotherium*" is still commonly used in interpretive materials. Fossil Butte NM preserves bones, teeth, and a nearly complete skeleton of this four-toed, small dog- or large cat-sized browsing horse. Etymology: *hyracos* (Greek word for a shrew) + *theros* (Greek meaning "wild animal").

ice age. General term for any period of increased glacial advance, particularly those occurring during the Pleistocene from 2.6 million years ago to 11,700 years ago.

igneous rock. One of the three main types of rock. Igneous rocks are made up of previously molten Earth materials. Volcanic rock is one type of igneous rock. Etymology: *ignis* (Latin meaning "fire").

***in situ*.** A term used to describe a fossil that is still "in place," not having been removed from where it was found. Etymology: *situs* (Latin meaning "location" or "place").

insolation. Term referring to *in*coming *sol*ar radi*ation*. This energy from the sun powers life on Earth. Times of low insolation at high northern latitudes (influenced by by **eccentricity**, tilt, and **precession**) supported the growth of continental ice sheets during "ice ages."

interglacial. Term used to signify times of retreating glaciers and relatively warm climate during the Pleistocene Epoch. Our current interglacial is termed the Holocene Epoch. Also see "glacial."

ion. An atom or molecule having a positive or negative charge that attracts or repels other ions.

isotope. A variety of an element that has the same number of protons but a different number of neutrons. Named by the total number of neutrons and protons in the nucleus, for example: Carbon-14 or Argon-40.

Kalobatippus. Relatively large and long-legged three-toed, browsing horse that lived during the Miocene. Found at Agate Fossil Beds NM and the "upper" John Day Formation paleoecosystems of John Day Fossil Beds NM. Etymology: *stilt walking horse.*

Knightia. Genus of small herring-like fish. It is the most common fossil fish at Fossil Butte NM and may be the most common articulated (not broken apart) vertebrate fossil in the world. Etymology: named after paleontologist Wilbur Clinton Knight.

lacustrine. Refers to materials or processes associated with a lake.

lahar. A volcanic mudflow. Often occurs when volcanic activity (or sometimes just heavy rain) melts snow or ice on a volcano, which then mixes with volcanic ash and mud that cascades down mountains at high rates of speed. Excellent mechanism for rapid burial.

lava. Still-molten or solidified material erupted from a volcano onto Earth's surface.

law. An empirical generalization: laws state what, under certain conditions, will happen (Scott, 2004) used to predict what might happen but do not explain how something happened.

locality. A documented geographic area, or defined site where fossils were collected. The National Park Service strives to maintain fossil localities in good condition.

macrofossil. A body or trace fossil visible to the naked eye. Compare to **microfossil**.

member. Subdivision of a named geologic **formation.**

Menoceras. Small (3 to 4 ft; about 1 m) tall rhinoceros common during the Miocene. The most common animal in the Agate Fossil Beds NM bone bed. Etymology: *meno* (Greek meaning "force" or "strength") + *keros* (Greek meaning "horn").

"*Merychippus*." Genus of tridactyl early and middle Miocene horses. One of the first **hypsodont** horses, and thus was commonly thought of as the first true grazing horse. Found in the Mascall paleoecosystems of John Day Fossil Beds NM. Etymology: *meryco* (Greek meaning "a ruminant" [cud-chewer]) + *hippos* (Greek meaning "horse").

mesodont. Describes a tooth that is not much taller than it is wide. Etymology: *mesos* (Greek meaning "middle") + *odon* (Greek meaning "tooth"). Compare to **brachydont** and **hypsodont**.

Mesohippus. Large collie-sized, three-toed horse common during the Oligocene. Very common in Badlands NP and John Day Fossil Beds NM, also found in Florissant Fossil Beds NM. Etymology: *meso* (Greek meaning "middle") + *hippos* (Greek meaning "horse").

metamorphic rock. One of the three main types of rock. Metamorphic rocks are have been altered by high temperature and/or pressure. Etymology: *meta* (Greek meaning "change") + *morpho* (Greek meaning "shape").

microfossil. A fossil, frequently microscopic, or otherwise hard to observe with the naked eye. Plant pollen and **Foraminifera** are common microfossils mentioned in this manual.

mineral. An inorganic solid with a defined composition and structure. Minerals are made up of elements. Rocks are made up of minerals.

Miohippus. Large collie-sized genus of three-toed horse common in Oligocene rocks of John Day Fossil Beds NM and Badlands NP. Originally named for a specimen found in the John Day Formation of John Day Fossil Beds NM. Etymology: *mio* (Greek meaning "less") + *hippos* (Greek meaning "horse").

molds/casts/impressions. Fossils formed when sediment covers the remains forming an impression or mold. When the organism rots away, the void (mold) can be filled with sediment, creating a cast of the original organism.

Moropus. Large, bizarre, clawed herbivore, from a now-extinct family, common during the Miocene. About the size and shape of a giraffe, with the head of camel and sloth-like claws, but distantly related to horses. The second most common animal in the bone beds of Agate Fossil Beds NM. Also common in similarly-aged rocks of John Day Fossil Beds NM.

mosasaur. Large (up to about 60 ft or 18 m) predatory marine reptiles that lived during the Mesozoic Era. They were likely the top of the Western Interior Seaway food chain. Mosasaur fossils are found in the Pierre Shale and Fox Hills Formation of Badlands NP. Etymology: *mosa* (refers to Meuse River in Holland where type specimen was found) + *sauros* (Greek meaning "reptile").

Nannippus. Genus of small, tridactyl, hypsodont horse, that lived from the late Miocene through Pliocene. Found in the Rattlesnake paleoecosystems of John Day Fossil Beds NM. Etymology: *nanus* (Latin meaning "dwarf") + *hippos* (Greek meaning "horse").

Neohipparion. Genus of large, late-Miocene, functionally monodactyl grazing horse. Found in the Rattlesnake paleoecosystems of John Day Fossil Beds NM. Etymology: *neos* (Greek meaning "new," "young," or "recent) + *hippos* (Greek meaning "horse") + *arion* (Greek suffix meaning "dimunitive").

neutron. An uncharged particle found in the nucleus (center) of an **atom**.

oreodont. Very diverse, now extinct, group of herbivorous animals generally about sheep-sized. Common in Oligocene and Miocene rocks throughout the American West, particularly at John Day Fossil Beds NM and Badlands NP. Etymology: *oreo* (Greek meaning "mountain" [not "chocolate cookie"!]) and *odon* (Greek meaning "tooth").

orogeny. A mountain building event. Etymology: *oro* (Greek meaning "mountain") + *geny* (French meaning "mode of production").

Orohippus. Genus of small dog-sized, four-toed, browsing horse found in the Clarno paleoecosystems of John Day Fossil Beds NM. Etymology: *oro* (Greek meaning "mountain") + *hippos* (Greek meaning "horse"). Likely refers to the peaks on the back teeth of *Orohippus*.

Palaeocastor. Large terrestrial beaver relatives that lived during the late Oligocene and early Miocene. Their distinctive spiral burrows are called *Daemonelix*, and are on display at Agate Fossil Beds NM. Etymology: *paleo* (Latin meaning "ancient") and *castor* (Latin name for "beaver").

paleosol. An ancient soil layer preserved in the geologic record. Paleosols hold many clues for reconstructing paleoecosystems. They can be indicators of average temperature, precipitation, and vegetation cover. Etymology: *paleo* (Greek meaning "ancient") + *solum* (Latin meaning "bottom," "ground," or "soil").

Parahippus. Genus of three-toed horse, from late Oligocene or early Miocene. Found within John Day Fossil Beds NM and Agate Fossil Beds NM. Etymology: *para* (Greek meaning "beside" or "near") + *hippos* (Greek meaning "horse").

period. A division of geologic time. The Cenozoic fossil parks span the Paleogene and Neogene periods. Together, those periods were previously referred to as the "Tertiary," a term no longer officially approved by the International Commission on Stratigraphy. **Epochs** make up **periods** make up **eras** which make up **eons**. For example the Miocene Epoch is part of the Neogene Period, which is part of the Cenozoic Era, which is part of the Phanerozoic Eon.

perissodactyl. An odd-toed ungulate (hooved mammal) including horses zebras and rhinos, representing a much smaller diversity today than during the Paleogene, in particular. Etymology: *perisso* (Greek meaning "odd-numbered") and *dactylo* (Greek meaning "finger").

permineralization. A fossilization process in which minerals fill in the pore spaces of an organism's hard parts.

petrified. Describes a fossil at least partially "turned to stone." Fossils may be petrified if organic material has been replaced by minerals, pore spaces filled by minerals, or both.

physical weathering. Process by which rocks or other Earth materials are physically broken into smaller pieces through erosion by wind, water, or gravity.

phytolith. Small accumulations of the element silica, secreted by plants. Grass phytoliths form a skeleton that lends shape to grasses' leaves. Phytoliths from different type of plants have different shapes, making them a reliable indicator of vegetation found in an area even if no other plant fossils exist. Etymology: *phyton* (Greek meaning "plant") + *lithos* (Greek meaning "stone").

plate tectonics. The geologic theory that Earth's outer hard shell is broken into many large (continent- and ocean-sized) plates. Volcanic eruptions, earthquakes, and deformation of rock layers occur where plates crash together, pull apart, or slide past one another.

Pliohippus. Genus of large, hypsodont, grazing horse. Later populations where monodactyl. *Pliohippus* was a late Miocene genus and is found in the Rattlesnake paleoecosystems of John Day Fossil Beds NM. Etymology: *pleion* (Greek meaning "more") + *hippos* (Greek meaning "horse").

precession. A description of where Earth's north-south axis (connecting the north and south poles) is pointed. Changes in precession are like a wobbling top. Precession is one of the three characteristics of Earth's orbit (along with **eccentricity** and tilt) that influence climate over periods of thousands of years.

principle of faunal succession. A concept in paleontology that fossil plants and animals occur in a definite and recognizable sequence. This concept makes absolute dating possible even when radioactive minerals are not present.

principle of superposition. Geologic concept stating that sedimentary rocks that have not been overturned, the older layers are at the bottom, and the younger layers are at the top—like a stack of pancakes coming off the griddle.

prospecting. A method paleontologists use to discover fossils. Erosional features such as stream beds or washes are investigated for fossil fragments.

proton. A positively-charged particle in the nucleus (center) of an atom.

quarrying. A method paleontologists use to discover fossils. Like stone quarries, excavations continue at one locality, where there are a large number of fossils in a relatively small area.

radioactive. Describes an isotope with an unstable arrangement of **protons** and **neutrons** that undergoes **radioactive decay** to an **isotope** with a stable arrangement of protons and neutrons.

radioactive decay. The changing of a radioactive parent isotope to a stable daughter isotope. Radioactive decay occurs at a constant measureable rate, making it a great rock clock.

radiometric dating. Determining the age of geologic material in years based on **radioactive decay**.

rain shadow. A dry area on the lee side of a mountain range, caused when high mountain areas block rain-bearing weather systems.

recrystallization. A fossilization process in which unstable crystal structures change into more stable crystal structures over time, usually while buried. The transition of the carbonate mineral aragonite to calcite in shells is a common example.

relative dating. Age-dating technique whereby fossil **assemblages**, the **principle of faunal succession**, and the **principle of superposition** are used to determine the age of a fossil compared to another fossil or rock layer. An absolute numerical age is not assigned, although a range may be suggested.

replacement. A fossilization process in which all of the original organic material is replaced by minerals, literally turning an organism to stone.

rock. An assemblage of minerals into a solid mass. An important tangible in every fossil park. Minerals are made up of elements. Rocks are made up of minerals.

sandstone. A sedimentary rock composed of sand-sized grains. Typically deposited in ocean, river, or eolian environments.

savannah. An ecosystem with grass cover and scattered trees that do not form a canopy. The African Serengeti is a modern example.

scrubland. An ecosystem with sparse, short "scrubby" vegetation.

sedimentary rock. One of the three main types of rock. Can be made up of rock fragments (**clasts**) or material precipitated from solution. Etymology: *sedimentum* (Latin meaning "a settling").

shale. A very fine-grained sedimentary rock with grains smaller than 0.002 in. (1/16 mm). Claystones and siltstones can be called shales if they split into layers.

shrubland. An ecosystem dominated by low brushy shrubs, such as sage brush, usually surrounded by grasslands and some small patches of trees. Short grasslands are called "steppe."

siltstone. A sedimentary rock composed of silt-sized grains. If it splits into layers, it is called a shale.

species. The most precise rank in the taxonomic classification for organisms. The genus and species together form the standard nomenclature for a living or fossil organism, with the genus capitalized and listed first. For example, the genus and species of humans is *Homo sapiens.* Biologically, the term commonly refers to populations that can interbreed successfully. See "taxonomy."

strata. Layers of sedimentary rock distinguishable from other layers above and below, also called "beds." Plural of the word *stratum*.

stratigraphy. Study and description of the sequence of rock layers (**strata**) through time.

stratigraphic column. A graphic representation of the rock layers in an area, arranged chronologically from youngest at the top to oldest at the bottom.

subduction. Geologic process where an oceanic and continental plate collide. The more dense oceanic crust sinks (subducts) beneath the less dense continental crust. Subduction zones along the West Coast fueled volcanoes that spewed erupted material over John Day Fossil Beds NM. Changes in the angle of subduction are thought to be responsible for the formation of the Rocky Mountains.

taphonomy. Study of what happens to animal or plant remains after the organism dies. Etymology: *taphos* (Greek meaning "grave") + *nomy* (Greek meaning "knowledge, or science, of").

taxonomy. Classification of organisms based on definable characteristics. Etymology: *taxon* (Greek meaning "classification") + *nomy* (Greek meaning "knowledge, or science, of"). The basic taxonomic classification has a hierarchy of ranks (from most general, to most specific): Kingdom, Phylum, Class, Order, Family, Genus, Species. Some taxonomists utilize additional ranks between the major ones listed here. A helpful paleontology-themed mnemonic could be: **K**nowledgeable **P**aleontologists **C**arefully **O**rganize **F**ossil **G**roups **S**ystematically.

theory. A well-substantiated explanation of some aspect of the natural world that can incorporate facts, laws, inferences, and tested hypotheses (National Academy of Sciences, 1998). Theories are the capstone of scientific knowledge.

thrust fault. A break in Earth's crust, resulting from compressional (pushing together) forces, with a shallow angle (less than 45°) where rock layers above the fault have been shoved, or thrust, up and over lower rock layers. Sometimes the upper layers can move long distances. One of the deformation processes that formed the Rocky Mountains.

titanothere. Huge rhino-like herbivorous beast, characteristic of the Eocene, that inhabited the greenhouse ecosystems of the Cenozoic fossil parks (Fossil Butte NM, John Day Fossil Beds NM, Badlands NP, and Florissant Fossil Beds NM). Went extinct at the Eocene-Oligocene boundary. Etymology: *titan* (Greek god; symbolic of brute force and large size) + *theros* (Greek meaning "wild animal").

topography. The general shape of the land. Etymology: Greek meaning “describing a place” (*topos* meaning “place” + *grapho* meaning “write”)

trace fossil. Physical evidence of an organism's activity rather than any part of the organism itself: footprint, trackway, burrows, dens, root traces, even poop are all trace fossils. Trace fossils help animate body fossils.

tridactyl. Describes an animal having three toes or fingers. Etymology: *tres* (Latin meaning “three”) + *dactylo* (Greek meaning “finger”)

unaltered remains. A fossilization process in which the original organic remains are unaltered such as in amber. Some of the fish scales at Fossil Butte NM are unaltered. Fossil teeth at the Cenozoic fossil parks may also be unaltered.

weather. Short-term, daily changes in temperature, precipitation, barometric pressure. Climate change and global weirding affect weather patterns.

vestigial. Describes a part of an animal’s body that was once prominent, but has since been reduced in size and no longer useable. The index, ring, and pinky “fingers” and corresponding “toes” of horses are now vestigial, but once all three touched the ground along with the middle digit. Etymology: *vestigium* (Latin meaning “footprint,” “trace,” or “mark”).

volcaniclastic. Clastic sediment mixed with volcanic debris such as ash or eroded volcanic rocks.

woodland. A low-density, open forest often with a shrubby or grassy understory.

APPENDICES

Appendix A. Other NPS areas that preserve fossils from the Paleogene and Neogene periods (the "Tertiary").

There are more than 224 National Park Service areas that preserve fossil resources. The Cenozoic fossil parks (in bold below) were established to conserve and interpret fossils from the Eocene, Oligocene, Miocene, and Pliocene epochs. Western parks (not including Alaska) that also preserve fossils from these time periods are listed below.

NPS Unit	State	Paleocene	Eocene	Oligocene	Miocene	Pliocene
Big Bend NP	Texas	✓	✓	✓	✓	✓
Grand Teton NP	Wyoming	✓	✓	✓	✓	✓
Santa Monica Mtns. NRA	California	✓	✓	✓	✓	
Bryce Canyon NP	Utah	✓	✓	✓		
Capitol Reef NP	Utah	✓	✓			
Cedar Breaks NM	Utah	✓	✓			
Theodore Roosevelt NP	N. Dakota	✓	✓			
John Day Fossil Beds NM	Oregon		✓	✓	✓	
Mount Rainier NP	Washington		✓	✓	✓	
Olympic NP	Washington		✓	✓	✓	
Death Valley NP	California		✓		✓	
Badlands NP	S. Dakota		✓	✓		
Glacier NP	Montana		✓	✓		
Scotts Bluff NM	Nebraska		✓	✓		
Florissant Fossil Beds NM	Colorado		✓			
Fossil Butte NM	Wyoming		✓			
Yellowstone NP	Wyoming, Idaho, Montana		✓			
Rocky Mountain NP	Colorado			✓	✓	
Niobrara NSR	Nebraska			✓	✓	✓
Alibates Flint Quarries NM	Texas				✓	✓
Lake Meredith NRA	Texas				✓	✓
Point Reyes NS	California				✓	✓
Redwood N&SP	California				✓	✓
Agate Fossil Beds NM	Nebraska				✓	
Mojave NPres	California				✓	
Nez Perce NHP	Idaho, Montana, Oregon, Washington				✓	
Yosemite NP	California				✓	
Hagerman Fossil Beds NM	Idaho					✓
Montezuma Castle NM	Arizona					✓
Petrified Forest NP	Arizona					✓

Appendix B. Additional references for "digging deeper."

There are numerous online resources for National Park Service interpretation, geology, and paleontology. Here are a few I find helpful. For links to climate change references, refer to Box 7.5. Addresses are current as of April, 2010.

Cenozoic fossil parks' websites. Fossil Butte NM *www.nps.gov/fobu*; John Day Fossil Beds NM *www.nps.gov/joda*; Badlands NP *www.nps.gov/badl*; Florissant Fossil Beds NM *www.nps.gov/flfo*; Agate Fossil Beds NM *www.nps.gov/agfo*; Hagerman Fossil Beds NM *www.nps.gov/hafo*.

Badlands NP Views Module. Interactive multimedia introduction to the park. *www.nature.nps.gov/views/layouts/Main.html#/Views*

Florissant Fossil Beds NM Views Module. Interactive multimedia introduction to the park. *www.nature.nps.gov/views/layouts/Main.html#/Views*

Florissant Fossil Beds NM Fossil Database. Comprehensive database of described fossil specimens from what is now the park. *http://planning.nps.gov/flfo*

John Day Fossil Beds NM Virtual Tour. Interactive multimedia introduction to the park. *www.nps.gov/features/joda/*

National Science Foundation Earth Science Literacy Principles. Document establishes the "big ideas" the public should know about Earth Science. Many of the principles read like interpretive themes. *www.earthscienceliteracy.org*

Paleobiology Database. Search for information about fossil taxonomy, localities, or geologic formations. Plot information on maps. *http://paleodb.org*

Paleontology Portal. General fossil info based on geographic location or geologic time. *www.paleoportal.org*

Ron Blakey's Paleogeographic Reconstructions. A wide array of regional and global paleogeographic reconstructions from many different geologic time periods, created by Ron Blakey (Northern Arizona University Department of Geology. Many of Blakey's reconstructions were used throughout this manual. *http://jan.ucc.nau.edu/~rcb7/index.html*

University of California-Berkeley Museum of Paleontology. Vast online paleontology exhibits, including information regarding evolution. *www.ucmp.berkeley.edu*

NPS Natural Resource Management Reference Manual #77. Paleontological resource information for resource managers: *www.nature.nps.gov/rm77/paleo.cfm*

NPS Paleontology Program. Basic, but somewhat dated, information regarding scope and significance of NPS paleontology. *www.nature.nps.gov/geology/paleontology*

NPS Park Paleontology Newsletter. Published 1999-2004. *www.nature.nps.gov/geology/paleontology/newsletter.cfm*

U.S. Geological Survey National Geologic Map Database (NGMDB). Catalog of geologic mapping *http://ngmdb.usgs.gov*

U.S. Geological Survey Geologic Names Lexicon (GEOLEX). Geologic unit nomenclature and summary. *http://ngmdb.usgs.gov/Geolex/geolex_home.html*

U.S. Geological Survey Geographic Names Information System (GNIS). Search for place names and geographic features, and plot them on topographic maps or aerial photos. *http://gnis.usgs.gov*

U.S. Geological Survey GeoPDFs. Download searchable PDFs of any topographic map in the United States. *http://store.usgs.gov* (click on "Map Locator").

U.S. Geological Survey Publications Warehouse. Many USGS publications are available online. *http://pubs.usgs.gov*

U.S. Geological Survey Tapestry of Time and Terrain. Descriptions of physiographic provinces. *http://tapestry.usgs.gov/Default.html*